NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2082

A REVIEW OF INFORMATION ON THE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS AT LOW TEMPERATURES

By K. O. Bogardus, G. W. Stickley, and F. M. Howell

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SUMMARY

The available sources of data on the mechanical properties of aluminum alloys at low temperatures are listed and a summary of the material to be found in each source is given.

From a review of the data presented and the conclusions expressed by the authors of the articles reviewed, general conclusions regarding the aluminum alloys used commercially in this country are drawn.

INTRODUCTION

Many investigators have reported that aluminum alloys in general exhibit not only higher tensile and yield strengths at low temperatures but also no loss of ductility. No evidence of embrittlement at low temperatures has been found in the commercial aluminum alloys but, in spite of this fact, questions concerning this subject arise from time to time.

For this reason an attempt has been made to summarize briefly herein the available information on the mechanical properties of aluminum alloys at temperatures ranging from normal room temperature down to the temperature of boiling liquid hydrogen, -423° F. Although no claim is made to absolute completeness, an attempt has been made to include all data available, starting with a pioneer report on this subject by Sir Robert Hadfield in 1905. The items in this review are arranged in the order in which they were published or became available, in case they were never published. One of the most extensive investigations is the series of tensile tests carried out at the Aluminum Research Laboratories on a large number of commercial aluminum alloys at temperatures ranging down to -320° F.

The kinds of tests used by the various investigators included tensile, hardness, impact, and fatigue.

A summary similar to this was published in 1942 as NACA TN 843. All references in that summary have been reviewed again, and are included in this enlarged summary along with additional data, much of which has become available since that time.

For convenience, an index of the authors of the various references is included at the end of this summary.

SOURCES OF DATA AND ABSTRACTS

1. Hadfield, R.: Experiments Relating to the Effects on Mechanical and Other Properties of Iron and Its Alloys Produced by Liquid Air Temperatures. Jour. Iron and Steel Inst., vol. 67, 1905, p. 147. (As reported in "The Mechanical Properties of Metals at Low Temperatures: Part 2 - Non-ferrous Materials," by E. W. Colbeck and W. E. MacGillivray. Trans. Institution Chemical Engineers, vol. 11, Nov. 29, 1933, p. 107.)

Sir Robert Hadfield, in the course of his investigation of iron and its alloys, tested aluminum of 99.5 percent purity at the temperature of liquid air.

He reports the following values:

Temperature	Tensile strength (psi)	Elongation (percent)
Room	17,900	7
-309° F	33,600	27

2. Cohn, L. M.: Changes in the Physical Properties of Aluminum and Its Alloys with Special Reference to Duralumin. Elektrotechnik und Maschinenbau, vol. 31, 1913, p. 430.

Tests on an alloy of the duralumin type using CO_2 snow as the cooling medium gave the following results:

Temper	Temperature ($^{\circ}F$)	Tensile strength (psi)	Elongation (percent) (1)
Heat-treated	70	62,400	20.0
	32	64,400	20.0
	-5	64,800	21.7
	-110	67,300	22.5
Heat-treated and cold-worked	70	76,000	6.1
	32	75,300	6.9
	-5	76,000	7.0
	-110	78,000	6.8

[1]Gage length not given; probably 11.3 $\sqrt{\text{area}}$.

3. Sykes, W. P.: Effect of Temperature, Deformation, Grain Size and Rate of Loading on Mechanical Properties of Metals. Trans. Am. Inst. Mining and Metallurgical Engineers, vol. 64, 1920, p. 780.

This paper describes tests on an aluminum alloy containing 3 percent copper, 0.42 percent iron, and 0.21 percent silicon in the form of wire 0.025 inch in diameter. The results were as follows:

Temper	Temperature ($^{\circ}F$)	Tensile strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)
Annealed at 300° C (572° F) for 30 min	77	21,900	8.60	68
	-58	24,000	15.50	70
	-301	36,500	21.80	44
61-percent reduction	77	51,000	3.12	52
	-301	59,000	7.80	35
92-percent reduction	77	49,500	2.03	32
	-58	49,000	3.10	--
	-301	63,000	6.00	28

4. Anon.: The Effect of Low Temperature on Some Aluminum Casting Alloys. Metallurgy Dept., NPL, July 1917. Reports of the Light Alloys Sub-Committee, British ACA, 1921, pp. 92-106.

The following paragraph is quoted from the summary report of tests made at the National Physical Laboratory in England using sand-cast and chill-cast aluminum alloys of the types commonly used during World War I, for aircraft-engine castings:

> "The results of the tests indicate clearly that there is no marked decrease in the strength of any of these alloys when they are exposed to low temperatures, either while the alloys are at the low temperatures or when they are subsequently allowed to regain ordinary temperatures. On the contrary, it is found that at these low temperatures the alloys are markedly stronger, but that the strength becomes normal when they are again raised to ordinary atmospheric temperature."

The following results are listed:

Composition	Temperature (°F)	Chill-casting		Sand-casting	
		Tensile strength (psi)	Elongation in 2 in. (percent)	Tensile strength (psi)	Elongation in 2 in. (percent)
2.5 percent Cu, 12.5 percent Zn	Room	25,800	3.5	23,700	2.8
	-112	31,500	10.0	24,000	2.8
	-301	33,100	8.0	24,300	2.8
14 percent Cu, 1 percent Mn	Room	23,700	1.0	13,700	1.0
	-112	27,500	1.2	16,600	1.0
	-301	33,800	1.2	18,100	1.2
8 percent Cu, 1 percent Mn	Room	24,400	2.2	11,600	1.5
	-112	31,000	3.8	12,500	1.0
	-301	31,000	3.2	13,000	1.0
12 percent Cu	Room	21,700	1.5	15,400	1.0
	-112	19,200	1.0	18,000	1.0
	-301	23,100	1.5	17,900	1.5
7 percent Cu, 1 percent Zn, 1 percent Sn	Room	19,600	3.5	16,100	3.0
	-112	19,200	4.7	16,800	3.0
	-301	24,400	4.0	20,900	3.0

5. Rosenhain, W., Archbutt, S. L., and Hanson, D.: Eleventh Report to the Alloys Research Committee: Some Alloys of Aluminum. The Institution of Mech. Engineers Eleventh Alloys Res. Rep., Aug. 1921.

The authors tested three wrought alloys at -112° F. The results of these tests were as follows:

Alloy	Temperature (°F)	Tensile strength (psi)	Yield strength (psi)	Elongation in 2 in. (percent)
3.0 percent Cu, 20.0 percent Zn	59	59,600	37,400	18.0
	-112	65,600	42,300	13.0
2.5 percent Cu, 20.0 percent Zn 0.5 percent Mg, 0.5 percent Mn	59	91,100	48,300	9.0
	-112	98,100	79,300	12.0
Duralumin	59	56,700	31,800	25.5
	-112	58,500	30,600	26.5

The authors make the following statement:

"In no case can it be said that the alloys are appreciably affected by the low temperature."

6. Guillet, L., and Cournot, J.: Sur la variation des propriétés mécaniques de quelques métaux et alliages aux basses températures. Revue de metallurgie, vol. 19, pt. I, 1922, p. 215.

Brinell hardness and Guillery impact tests at low temperatures gave the following results:

Alloy	Temperature (°F)	Brinell hardness	Guillery impact resistance
Commercial Al (0.25 percent Si, 0.6 percent Fe)	70	24	11.2
	-4	25	10.6
	-112	24	11.2
	-166	39	----
	-301 to -310	53	13.1
Duralumin	70	101	5.0
	-4	96	5.6
	-112	101	5.0
	-166	107	----
	-301 to -310	129	5.6
Al (15 percent Zn)[1]	70	55	11.2
	-4	47	11.2
	-112	48	10.0
	-166	62	----
	-301 to -310	76	9.3

[1]No alloy of this type is used in the U.S.

7. Anon.: Physical Properties of Materials. I. Strengths and Related Properties of Metals and Wood. Second ed., Nat. Bur. Standards Circular No. 101, U.S. Govt. Printing Office, 1924.

This report gives the ratio of Young's modulus at 0° absolute to that at 0° C for aluminum as being 1.44. This was taken from an article "Elasticity of Metals as Affected by Temperature" by A. Mallock in the Proceedings of the Royal Society of London, volume 95, series A, 1919, page 429.

8. Upthegrove, Clair, and White, A. E.: Available Data on the Properties of Non-Ferrous Metals and Alloys at Various Temperatures. Proc. A.S.T.M., vol. 24, 1924, pp. 88-127.

The authors refer to tests reported in this summary in item (5), Rosenhain, Archbutt, and Hanson, and say:

"Tension tests on three typical aluminum alloys at low temperatures, -112° F, showed no decrease in tensile properties."

9. Greaves, R. H., and Jones, J. A.: The Effect of Temperature on the Behaviour of Metals and Alloys in the Notched-Bar Impact Test. The Jour. Inst. Metals, vol. XXXIV, no. 2, 1925, pp. 85-101.

Cast aluminum (0.16 percent Si, 0.06 percent Fe) gave a steady rise in impact values from 26.8 foot-pounds at room temperature to 36.2 foot-pounds at -54° F. At -112° F results were variable, ranging up to 44.2 foot-pounds.

Duralumin was tested after quenching from 500° C both without and with aging. The aged material retained its strength at -4° F but declined about 4 percent in impact strength as the temperature dropped to -112° F. The unaged material increased about 6 percent at -4° F and -112° F.

10. Strauss, Jerome: Metals and Alloys for Industrial Applications Requiring Extreme Stability. Trans. Am. Soc. Steel Treating, vol. 16, 1929, pp. 191-225.

Tensile tests using liquid air as the cooling medium gave the following results:

Alloy	Temperature	Tensile strength (psi)	Yield strength (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)
Cast, 1.0 percent Cu, 0.8 percent Mn, 0.3 percent Si, 0.5 percent Fe	Room	18,100	7,600	8.8	10.2
	Liquid air	17,800	8,100	7.0	7.3
Cast, 0.2 percent Cu, 5.0 percent Si, 0.6 percent Fe	Room	17,300	9,200	4.9	5.2
	Liquid air	19,600	9,600	3.7	4.7
Duralumin	Room	57,800	35,400	26.5	27.0
	Liquid air	71,800	42,700	28.0	28.7

11. Schwinning, W., and Fischer, F.: Versuche über den Einfluss der Temperatur auf Kerbzähigkeit und Härte von Aluminiumlegierungen. Zeitschr. für Metallkunde, Bd. 22, Jan. 1930, pp. 1-7.

These authors report on hardness and impact tests on notched bars of Lautal and 99.5 percent aluminum. The following table summarizes their results:

Alloy	Temperature (°F)	Brinell hardness	Impact strength (m-kg/cm^2)
99.5 percent Al	68	30.4	4.0
	-105	36.0	---
	-306	----	6.1
Lautal	68	110	1.5
	-105	115	---
	-306	-----	1.7

12. Güldner, W. A.: Über die Kerbzähigkeit einiger Aluminiumlegierungen insbesondere bei tiefen Temperaturen. Zeitschr. für Metallkunde, Bd. 22, Aug. 1930, pp. 257-260.

This author found improvement in the impact behavior of a few aluminum alloys at -75° F.

13. Musatti, I.: Dynamic Properties of Magnesium Alloys. La Metallurgia Italiana, vol. 22, 1930, p. 1052.

Charpy impact tests of duralumin were made at several low temperatures. Test bars, 10 by 10 millimeters, with a 2-millimeter-deep, 2-millimeter-wide Mesnager notch of 1-millimeter radius were used.

Impact values are as follows:

Temperature	Impact (m-kg/cm^2)
15° C (60° F)	4.17
0° C (32° F)	4.15
-20° C (-4° F)	4.35
-50° C (-58° F)	4.90

14. Edwards, J. D., Frary, F. C., and Jeffries, Z.: The Aluminum Industry - Aluminum Products and Their Fabrication. Vol. II. McGraw-Hill Book Co., Inc., 1930, pp. 558-561.

On the basis of various reports, all of which are covered separately in this book, the authors make these observations:

> "When tested at low temperatures, aluminum alloys show increased tensile strength. Ductility, as measured by percentage of elongation in the tensile test, seems to remain about the same as at ordinary temperatures, or even to increase slightly."

15. Brombacher, W. G., and Melton, E. R.: Temperature Coefficient of the Modulus of Rigidity of Aircraft Instrument Diaphragm and Spring Materials. NACA Rep. 358, 1930.

The authors made measurements on wires with a torsion pendulum through the temperature range -20° to 50° C. They have determined the temperature coefficient of the modulus of rigidity for this temperature range and list the following values:

Alloy	Temper	Temperature coefficient
99.5 percent Al	Annealed	-100 to -135×10^{-5}
	Half-hard	-62
Duralumin	Heat-treated	-62
	Unknown	-46

16. Pester, Fr.: Die Festigkeitseigenschaften von electrischen Leitungsdrähten bei tiefen Temperaturen. Zeitschr. für Metallkunde, Bd. 22, Aug. 1930, pp. 261-263.

Tensile and bending tests were made of pure aluminum and Aldrey (0.5 to 0.6 percent Si, 0.3 percent Fe, and 0.4 percent Mg) in the form of wire at various low temperatures.

The tensile tests were carried out at 68°, 32°, -4°, -22°, and -76° F. The bending tests were carried out at 68°, -22°, and -76° F. Results of these tests are shown in the following table:

Alloy	Diam. of wire (in.)	Temperature (°F)	Tensile strength (psi)	Elongation (percent)	Reduction of area (percent)	Bending number (1)
Pure aluminum	0.083	68	27,000	2.3	80	17
		32	27,600	2.1	78	--
		-4	28,400	2.0	78	--
		-22	28,700	1.8	79	20
		-76	29,900	2.0	80	21
	.110	68	27,400	3.1	80	15
		32	28,200	3.0	80	--
		-4	29,000	3.0	81	--
		-22	29,300	2.9	80	17
		-76	30,300	2.7	79	18
	.142	68	24,900	3.1	80	18
		32	25,600	3.3	79	--
		-4	26,200	3.1	81	--
		-22	26,400	3.5	80	21
		-76	27,000	3.5	80	22
Aldrey (0.5 to 0.6 percent Si, 0.3 percent Fe, 0.4 percent Mg)	.083	68	47,400	6.4	55	12
		32	48,800	7.3	51	--
		-4	49,900	6.3	50	--
		-22	50,800	7.3	52	12
		-76	52,600	7.6	52	12
	.110	68	48,300	6.8	52	9
		32	------	7.5	57	--
		-4	50,800	7.7	52	--
		-22	51,500	8.0	52	6
		-76	53,200	8.2	57	7
	.142	68	49,200	7.1	50	8
		32	50,500	7.8	47	--
		-4	51,900	7.2	50	8
		-22	51,900	8.3	50	8
		-76	54,000	8.1	50	8

[1]The bending radius was 0.197 in. for the 0.083- and 0.110-in.-diameter wires and 0.295 in. for the 0.142-in.-diameter wire.

Concerning the results of these tests the author says:

"All . . . materials exhibit an increase of the tensile strength with decreasing temperature."

"Aluminum wires of 2.1 and 2.8 mm [0.083 and 0.110 in.] diameter show a decrease in elongation with decreasing temperature of 13.5 percent, the 3.6 mm [0.142 in.] aluminum wire shows an increase of the elongation of 13.5 percent."

"Aldrey wire of 2.1 mm [0.083 in.] diameter shows an increase in elongation of 18.5 percent; the 2.8 mm [0.110 in.] wire shows an increase of 20.6 percent and 3.6 mm [0.142 in.] wire 14.1 percent."

"None of the . . . materials investigated show an appreciable increase or decrease of the reduction in area with decreasing temperature."

". . . it was possible to conclude that the bending numbers are influenced by the temperature."

"In general they [the bending numbers] increase with decreasing temperature."

17. Templin, R. L., and Paul, D. A.: The Mechanical Properties of Aluminum and Magnesium Alloys at Elevated Temperatures. Symposium on Effect of Temperature on the Properties of Metals, issued jointly by A.S.T.M. and A.S.M.E., June 23, 1931, pp. 198-217.

Tests at the Aluminum Research Laboratories[1] made on various aluminum alloys cooled in a mixture of solid CO_2 and ether gave the following results:

[1]See item (61) for additional tests made at the Aluminum Research Laboratories.

Alloy, temper, and form	Temper- ature (°F)	Tensile strength (psi)	Yield strength (psi) (1)	Elongation in 2 in. (percent)
2S-O rod	70 -110	13,250 15,180	4,150 4,150	41.5 47.5
2S-H18 rod	70 -110	23,460 24,720	19,700 21,350	16.0 18.0
3S-H18 rod	70 -110	28,730 31,940	25,300 28,200	10.0 12.5
17S-O rod	70 -110	27,480 29,290	9,800 10,500	22.0 26.0
17S-T4 rod	70 -110	68,000 70,000	45,500 46,500	15.0 16.0
25S-T6 rod	70 -110	61,600 63,660	36,500 37,000	20.0 20.6
51S-O rod	70 -110	15,670 18,020	5,600 6,200	31.0 36.0
No. 43, sand-cast	70 -110	20,050 20,180	8,000 8,000	4.5 5.0
No. 195-T4, sand-cast[2]	70 -110	35,145 36,830	23,250 25,200	4.5 4.0

[1]Offset, 0.1 percent.
[2]Heat-treated.

On the basis of these tests and test results published by others, the authors conclude that:

> "Temperatures as low as that of liquid air (-320° F) do not have a harmful effect on aluminum alloys. On the contrary, at such temperatures both the strength and ductility of aluminum alloys seem to be higher than at ordinary temperatures."

18. Russell, H. W.: Effect of Low Temperatures on Metals and Alloys. Symposium on Effect of Temperature on the Properties of Metals, issued jointly by A.S.T.M. and A.S.M.E., June 23, 1931, pp. 486-508.

The author summarizes the results of investigations made by others between 1905 and 1931. Most of the pertinent data of his paper have been covered in this summary by items (3), Sykes; (6), Guillet and Cournot; (10), Strauss; (15), Brombacher and Milton; and (17), Templin and Paul.

The author also lists the coefficient of thermal expansion of aluminum at -148° F as 0.0000182 compared with 0.00002265 at 32° F (computed from International Critical Tables, vol. II, McGraw-Hill Book Co., Inc., 1927, p. 459).

19. Bollenrath, Franz, and Nemes, Joan: The Behavior of Various Light Metals at Low Temperatures. Metallwirtschaft, vol. X, no. 31, 1931, pp. 609-613; vol. X, no. 32, 1931, pp. 625-630. (As taken from Chemical Abstracts, vol. 26, Jan.-April 1932, p. 58.)

Tensile and impact tests of seven forging alloys were made at temperatures as low as -310° F.

The authors state:

"The static tensile properties of all alloys examined rise considerably with lowering temperature, while the elongation and reduction do not change as much . . . . Silumin and Lautal behave differently from the other aluminum alloys. The increase in tensile strength at low temperatures is accompanied by a drop in yield point and elastic limit. In the dynamic tests, the specific impact energy is highest at moderately low temperatures for most of the alloys, while the elongation is practically constant . . . . Lowering the temperature does not have as much effect on the dynamic properties as on the static properties. All the alloys tested can be used at temperatures down to -190° C [-310° F]."

20. Matthaes, K.: Dynamische Festigkeitseigenschaften einiger Leichtmetalle. Zeitschr. für Metallkunde, Bd. 24, Aug. 1932, pp. 176-180.

The author made rounded-notch Charpy impact tests at -290° F.

He found that Scleron (1 percent Si, 4.5 percent Cu), rolled to 50,000-psi tensile strength, increased in impact resistance from 1.5 to 1.75 meter-kilograms per square centimeter at -290° F. Lautal (2 percent Si, 4.5 percent Cu), forged to 53,000-psi tensile strength, and duralumin, heat-treated to 65,000-psi tensile strength, increased in impact resistance down to -110° F, then fell back at -290° F to about the room-temperature value.

21. Sandell, Bert E.: Effect of Temperature upon the Charpy Impact Strength of Die-Casting Alloys. Trans. Am. Inst. Mining and Metallurgical Engineers, vol. 99, 1932, pp. 359-362.

The following results of Charpy impact tests of die-castings are given. Each value represents the mean of ten individual determinations.

Die-cast alloy	Temperature (°F)	Charpy impact value	
		Actual	(ft-lb/in.)
0.24 percent Cu, 5.11 percent Si, 1.89 percent Fe, 0.11 percent Zn, 0.22 percent Ni, 0.04 percent Mn, 0.01 percent Mg	0 32 70	4.80 4.94 5.73	76.80 79.04 91.68
0.12 percent Cu, 11.58 percent Si, 1.25 percent Fe, 0.28 percent Zn, 0.08 percent Mn, 0.03 percent Mg	0 32 70	3.50 3.69 3.76	56.00 59.04 60.16

The author reports:

"The two die-cast aluminum-silicon alloys exhibit no appreciable variation in impact strength from 0° to 500° F."

22. Bollenrath, Franz: On the Influence of Temperature on the Elastic Behaviour of Various Wrought Light Metal Alloys. The Jour. Inst. Metals, vol. XLVIII, no. 1, 1932, pp. 255-272.

In this article, the author is particularly interested in the modulus of elasticity and elastic limit of aluminum at temperatures as low as -310° F. He tested seven aluminum alloys, using a Martens optical extensometer. It is to be noted that the specimens were held at the testing temperature 110 hours before testing.

As taken from graphical representations the following values are derived:

Alloy	Temper	Temperature (°F)	Modulus of elasticity (psi)	Elastic limit (Offset, 0.01 percent) (psi)
Duralumin 681B, 3.64 percent Cu, 0.47 percent Mg, 0.57 percent Mn, 0.23 percent Si, 0.23 percent Fe	Aged at room temperature	75 -112 -310	10,000,000 10,400,000 10,800,000	29,200 33,400 44,800
Duralumin 681ZB, 4.21 percent Cu, 0.73 percent Mg, 0.63 percent Mn, 0.39 percent Si, 0.25 percent Fe	Aged at room temperature	75 -112 -310	10,200,000 10,600,000 10,900,000	49,800 56,900 64,000
Lautal, 4.21 percent Cu, 2.12 percent Si, 0.26 percent Fe	Aged 60 hr at 140° C	75 -112 -310	9,800,000 9,700,000 10,500,000	29,900 24,200 31,300
Silumin, 13.1 percent Si, 0.38 percent Fe	Annealed	75 -112 -310	9,400,000 9,400,000 8,700,000	12,800 13,900 10,000
Scleron, 3.0 percent Cu, 0.6 percent Mn, 0.25 percent Si, 0.27 percent Fe, 12.0 percent Zn, 0.1 percent Li	Aged at room temperature	75 -112 -310	9,800,000 10,200,000 10,700,000	40,500 48,300 56,900
Constructal 2, 1.2 percent Cu, 0.92 percent Mg, 0.5 percent Mn, 0.56 percent Si, 0.26 percent Fe, 0.5 percent Ti	Aged for 25 hr at 145° C	75 -112 -310	9,900,000 10,400,000 10,400,000	39,800 42,700 44,800
Constructal 87, 1.62 percent Mg, 1.24 percent Mn, 0.29 percent Si, 0.28 percent Fe, 6.87 percent Zn	Aged for 30 hr at 75° C	75 -112 -310	10,000,000 10,500,000 10,900,000	51,200 57,600 64,700

The author presents a formula for determining modulus at any temperature down to -310° F. The foregoing modulus values were not derived from the formula but are taken from plottings of actual test results.

In the use of the formula the author makes this observation:

> "Special reference may be made to the lines for the alloys Silumin and Lautal, for which a clear maximum value exists at a temperature of about -20° C [-4° F]. Both lower and higher temperatures cause a decrease of Young's modulus. There is little doubt that the behaviour of these two alloys is caused by the content of silicon. The re-increase for Lautal at yet lower temperatures is probably a consequence of alloyed copper. Microscopic examination shows no alteration of structure."

Concerning elastic limits at various low temperatures the author says:

> "These curves indicate a behaviour of the elastic limit, similar to that of modulus of elasticity."

23. Anon.: Aluminum Alloys at Low Temperatures Proved to be Stronger. Daily Metal Reporter, vol. 30, no. 229, 1930, p. 8. (As reported from Metallurgical Abstracts, The Jour. Inst. Metals, vol. L, no. 3, 1932, p. 660.)

> "Comparative tests are described on alloys of the duralumin type (17S-T), on a propeller alloy (25S-T), and on 2S and 3S, two simpler alloys, at 24° C and -80° C in order to determine their suitability for aero construction. The low-temperature tests were carried out in a container cooled by a mixture of solid carbon dioxide and ether; they covered toughness, load-carrying capacity, and tensile strength, and were applied by specially designed machines. Both wrought and sand-cast alloys showed a definite increase in strength."

24. Colbeck, E. W., and MacGillivray, W. E.: The Mechanical Properties of Metals at Low Temperatures: Part 2 - Non-ferrous Materials. Trans. Institution Chemical Engineers, vol. 11, Nov. 29, 1933, pp. 107-123.

These British authors made tensile and Izod impact tests of aluminum of commercial origin, in the form of 1-inch round rolled bars at low temperature. The samples were annealed except in the case of "Y" alloy which was quenched from 968° F in boiling water and aged 1 hour at 212° F.

In reporting on their tensile tests they say:

"Aluminium shows a greater proportional change in ultimate strength than any of the other materials tested, a rise of well over 100 percent being found in this property at -180° C [-292° F]. This material remains very ductile over the whole range of temperature."

They report the following results:

Alloy and temper	Diameter of test piece (in.)	Temper-ature (°F)	Change from room-temperature value (percent)			
			Tensile strength	Proof stress	Elongation in 2 in.	Reduction of area
0.054 percent Si,	0.250	14	16	15	0	0
0.07 percent Fe	.250	-40	19	10	11	2
	.250	-112	21	-4	6	1
	.250	-184	44	-20	10	0
	.250	-292	112	2	22	-4
	.504	-292	140	---	26	-4
"Y" alloy,	.250	14	0	1	-6	-12
3.46 percent Cu,	.250	-40	3	0	2	-3
0.30 percent Si,	.250	-112	5	2	9	-9
0.45 percent Fe,	.250	-184	15	8	(1)	(1)
0.08 percent Mn,	.250	-292	30	8	26	18
1.86 percent Ni,	.540	-292	26	36	26	-5
0.76 percent Mg						

[1]Broke outside gage length.

In evaluating their tensile test results, the authors refer to results published by earlier investigators, most of which have been reported on previously in this summary.

"We confirm Pester's [2] results for aluminium at temperatures down to -80° C, namely that there is a definite increase in the tensile strength and elongation and very little change in the reduction in area over this range."

"The percentage increase in the tensile strength of "Y" alloy between 20° C and -180° C is similar to that quoted by Russell [3] for duralumin, but this light alloy shows a definite falling

[2]Fr. Pester (see item (16) of this summary).
[3]H. W. Russell (see item (18) of this summary).

off in the reduction of area at the lowest temperatures whereas Russell's figures show a slight increase; however, the elongation figures of both alloys show some improvement at -180° C."

Concerning their Izod impact tests, made at -40°, -184°, and -292° F, the authors say that the increases in toughness at the lower temperatures were appreciable for the pure aluminum but for "Y" alloy there was little alteration between room temperature and -292° F.

The following test results are given:

Temperature (°F)	Si, 0.05 percent, Fe, 0.07 percent		"Y" alloy (a)	
	Impact (ft-lb)	Percentage increase over room temperature	Impact (ft-lb)	Percentage increase over room temperature
Room	19.0	--	[b]7.0	--
-40	19.0	0	[b]7.5	7
-112	20.0	5	[b]7.5	7
-184	21.0	10	[b]7.5	7
-292	27.0	42	[b]8.0	14

[a]Composition, 3.46 percent Cu, 0.30 percent Si, 0.45 percent Fe, 0.08 percent Mn, 1.86 percent Ni, 0.76 percent Mg.
[b]Broken clean through.

25. Johnson, J. B., and Oberg, Ture: Mechanical Properties at Minus 40 Degrees of Metals Used in Aircraft Construction. Metals and Alloys, vol. 4, March 1933, pp. 25-30.
(See also: Gillett, H. W.: Impact Resistance and Tensile Properties of Metals at Subatmospheric Temperatures. A.S.T.M., Aug. 1941.)

Tensile, Brinell hardness, Izod impact, and rotating-beam fatigue tests were made in a mechanically refrigerated room at Wright Field.

The authors report:

". . . the ductility as measured by elongation and reduction of area is practically unaffected by the change from room temperature to -40° C [-40° F]. There is an increase in tensile strength but in the case of the cast alloys this increase is too small to have any significance. Fatigue limits are slightly higher at the low temperatures."

"The fatigue properties of the notched specimens are raised [at -40° F] in about the same proportion as the unnotched specimens [in contrast to other metals]."

The following modulus-of-elasticity values are shown:

Alloy and Temper	Modulus, psi, at -	
	Room temperature	-40° F
25S-T6	10,400,000	10,800,000
17S-T4	10,000,000	10,000,000
17S[a]	10,300,000	10,300,000

[a]Special heat treatment.

They list the following results of tensile tests:

Alloy and temper	Temperature (°F)	Tensile strength (psi)	Yield strength (Offset, 0.2 percent) (psi)	Elongation in 4 diameters (percent)	Reduction of area (percent)	Izod impact (ft-lb) (a)	Endurance limit (psi)	Brinell hardness (3000 kg)
				Forging				
25S-T6	Room -40	55,500 58,500	30,000 31,500	16 13	22 20	13 13	[b]13,000 [b]16,000	102 105
	Room -40	60,600 66,000	37,400 39,800	21 17.5	27 31	-- --	------- -------	112 112
				Extruded bar				
17S-T4	Room -40	58,000 60,500	42,000 44,500	23 23.5	42.5 42	-- --	------- -------	112 ---
[c]17S	Room -40	67,000 69,000	59,000 58,000	14 13	31 31.5	-- --	------- -------	139 ---
				Castings				
[d]212	Room -40	24,500 26,600	------ ------	2.2 1.7	---- ----	-- --	[e]7,000 [e]9,000	82 89
[f]142	Room -40	39,500 39,500	------ ------	1.0 1.0	---- ----	-- --	[e]7,000 [e]8,000	121 115
[d]108	Room -40	21,300 23,300	------ ------	2.5 3.0	---- ----	-- --	[g]7,000 [g]7,000	64 66
[d]43	Room -40	18,700 18,400	------ ------	11.0 8.5	---- ----	-- --	[g]6,000 [g]7,000	45 44
(h d)	Room -40	21,700 21,700	------ ------	3 3	---- ----	-- --	[e]7,000 [e]8,000	65 72
(i d)	Room -40	25,100 24,300	------ ------	12.5 8.0	---- ----	-- --	[g]6,000 [e]7,000	58 59

[a]45° V-notch, 0.01-in. radius.
[b]Fatigue limit at 500,000,000 cycles.
[c]Special heat treatment.
[d]As-cast.
[e]Fatigue limit at 100,000,000 cycles.
[f]Aged 2 hr at 300° F.
[g]Fatigue limit at 200,000,000 cycles.
[h]Si, 0.10; Fe, 0.18; Cu, 7.76.
[i]Mg, 3.66; Si, 0.12; Fe, 0.15; Mn, 0.50; Cu, 0.02.

26. DeHaas, W. J., and Hadfield, R.: Phil. Trans. Roy. Soc. (London), ser. A, vol. 232, 1934, p. 297.
(As taken from "Report on Literature Survey on the Low Temperature Properties of Metals to October 1941," by A. E. White and C. A. Siebert. OSRD Rep. No. 281, Dec. 1941.)

The authors present the following test results of duralumin in the as-rolled condition:

Tensile property	Room temperature	-423° F
Tensile strength, psi	67,200	102,600
Yield strength, psi	50,200	78,600
Elongation in 2 in., percent	18.0	17.0
Reduction of area, percent	33.5	20.0

27. Schwinning, W.: Die Festigkeitseigenschaften der Werkstoffe bei tiefen Temperaturen. VDI Zeitschr. Jan. 1935, pp. 35-40.

The results given in this paper are tabulated as follows:

Alloy	Temperature (°F)	Tensile strength (psi)	Yield strength (Set, 0.2 percent) (psi)	Elongation in 25 cm (percent)	Fatigue strength (10^6 cycles) (psi)
Pure aluminum (99.15 percent), hard-drawn	68	21,000	18,600	14.0	12,000
	-40	23,000	19,800	11.3	12,800
Aldrey	68	42,000	37,000	12.7	16,000
	-40	44,500	38,000	11.6	18,500
Bondur	68	64,000	48,000	18.8	20,000
	-40	65,000	48,400	19.9	16,300
Duralumin 681B	68	61,500	49,000	16.9	18,000
	-40	63,000	49,600	15.0	18,000
Duralumin DM31	68	71,000	57,000	16.3	20,000
	-40	74,000	56,000	17.1	20,000

28. Boone, W. D., and Wishart, H. B.: High-Speed Fatigue Tests of Several Ferrous and Non-Ferrous Metals at Low Temperatures. Proc. A.S.T.M., vol. 35, pt. II, 1935.

Rotating-beam fatigue tests made on a high-speed fatigue machine in the cold room at Wright Field on duralumin (17S-T4) specimens indicate the following results:

Temperature (°F)	Endurance limit (1)	
	Unnotched specimens	Notched specimens
80	17,000	9,000
10	18,500	12,000
-20	20,500	------
-40	21,000	13,000

[1]Based on 50,000,000 cycles.

The authors state:

"In general, as the temperature was decreased the endurance limits of the metals increased. The stress concentration factors showed no consistent change."

29. Moore, H. F., Wishart, H. B., and Lyon, S. W.: Slow-Bend and Impact Tests of Notched Bars at Low Temperatures. Proc. A.S.T.M., vol. 36, pt. II, 1936.

Slow-bend tests and Izod impact tests of duralumin (17S-T4) were made in the cold room at Wright Field. Results were as follows:

Temperature (°F)	Energy for fracture (ft-lb)	
	Slow-bend tests	Izod impact tests
70	13.00	18.10
10	13.57	18.90
-20	13.37	20.10
-40	13.82	19.60

Concerning these tests the authors state:

"For . . . duralumin [17S-T4] the energy of fracture increases with lowering temperature."

30. Twenty-second Annual Report of the National Advisory Committee for Aeronautics. U.S. Govt. Printing Office, 1936; and Twenty-third Annual Report of the National Advisory Committee for Aeronautics. U.S. Govt. Printing Office, 1937.

These reports comment briefly on a program of tests carried out by the National Bureau of Standards in cooperation with the Bureau of Aeronautics on various aircraft metals at subzero temperatures. The program involved what appears to have been an extensive study of properties and impact resistance. Quoting from the Twenty-third Annual Report:

"The only important adverse effect of low temperature, down to -80° C (-112° F), is the decreased impact resistance of ferritic steels, which is in marked contrast to the aluminum alloys and the austenitic steels."

31. Anon.: Engineering Data on the Aluminum Alloys Used Structurally in Railroad Car Construction. Aluminum Co. of Am., Aluminum Res. Laboratories Rep. No. 287-M, March 9, 1938.

The values for tensile properties at low temperatures listed in this report are taken from the report by Templin and Paul reviewed in item (17) of this summary.

Concerning these values, this report says:

"Tests at the Aluminum Research Laboratories on five wrought aluminum alloys at -112° F show a consistent slight increase in tensile strength, yield strength and elongation when compared with room temperature properties."

The test results of slow-bend and Izod impact tests shown here are taken from a report by Moore, Wishart, and Lyon, reviewed in item (29) of this summary. Concerning these values, this report says:

"This [results of slow-bend tests] demonstrates clearly that there is no decrease in resistance to slow bending as the temperature decreases."

"These [impact] tests indicate clearly that there is no reduction in resistance to impact as the temperature decreases."

32. Bungardt, Karl: Dynamische Festigkeitseigenschaften von Leichtmetall-Legierungen bei tiefen Temperaturen. Zeitschr. für Metallkunde, Bd. 30, July 1938, pp. 235-237.

Fatigue bending tests and notched-bar impact tests were made of various aluminum alloys at -31° and -85° F.

For the fatigue bending tests, the specimens were cut from extruded rods 15 millimeters in diameter. The notched-bar impact tests were carried out on sheets 11 millimeters thick.

Alloy	Temperature (°F)	Endurance limit (psi) (1)	Alloy	Notched-bar impact value (m-kg/cm^2)
4.39 percent Cu, 1.08 percent Mg, 1.16 percent Mn, 0.46 percent Fe, 0.63 percent Si, 0.01 percent Ti	68 -31 -85	23,200 28,800 26,700	4.27 percent Cu, 1.22 percent Mg, 1.21 percent Mn, 0.37 percent Fe, 0.42 percent Si,	0.96 1.27 1.32
3.74 percent Cu, 0.91 percent Mg, 0.84 percent Mn, 0.47 percent Fe, 0.42 percent Si, 0.01 percent Ti	68 -31 -85	21,800 22,200 25,600	4.12 percent Cu, 0.66 percent Mg, 0.57 percent Mn, 0.36 percent Fe, 0.32 percent Si	1.94 2.21 2.37
0.03 percent Cu, 4.68 percent Mg, 0.26 percent Mn, 0.35 percent Fe, 0.15 percent Si, 0.007 percent Ti	68 -31 -85	19,200 23,900 26,700	4.97 percent Mg, 0.25 percent Mn, 0.20 percent Fe, 0.14 percent Si, 0.003 percent Ti	1.74 2.50 2.69
6.57 percent Mg, 0.18 percent Mn, 0.70 percent Fe, 0.11 percent Si, 0.007 percent Ti	68 -31 -85	25,200 25,700 26,300	0.01 percent Cu, 7.14 percent Mg, 0.22 percent Mn, 0.32 percent Fe, 0.15 percent Si, 0.003 percent Ti	1.30 1.50 1.63
0.04 percent Cu, 8.93 percent Mg, 0.28 percent Mn, 0.44 percent Fe, 0.12 percent Si, 0.01 percent Ti,	68 -31 -85	20,300 19,600 20,800	0.04 percent Cu, 7.73 percent Mg, 0.18 percent Mn, 0.40 percent Fe, 0.16 percent Si, 0.003 percent Ti, 0.98 percent Zn	1.88 1.88 1.86

[1]Rotating-beam machine using 20,000,000 cycles.

The author says:

"The fatigue bending strength of aluminum as well as magnesium alloys increases with lowering temperatures in the temperature range to -65°."

"With the exception of the aluminum-magnesium alloy with the highest magnesium content of 7.73 percent Mg and 0.98 percent Zn, in which the notched-bar impact value is unchanged, this property is increased in aluminum alloys by low temperatures to -65° [-85° F]."

33. Sharp, W. H.: Impact Tests at High and Low Temperatures of Aluminum Alloys Used in Railroad Car Construction. Aluminum Co. of Am., Aluminum Res. Laboratories Rep. No. 39 - 12, March 20, 1939; also reported in "A Summary of Results of Various Investigations of the Mechanical Properties of Aluminum Alloys at Low Temperatures," by E. C. Hartmann and W. H. Sharp. NACA TN 843, 1942.

A series of tests was made on 2-inch solid round rods subjected to the blow of a 500-pound tup striking at the center of a 36-inch span. The height of drop used in each case and the permanent sets, both at ordinary temperature and at -120° F, are given in the following table:

Alloy and temper	Height of drop of 500-lb tup (in.)	Permanent set (in.)	
		Rod at 75° F	Rod at -120° F
27S-T6	120	$4\frac{5}{8}$	$4\frac{3}{4}$
17S-T4	96	$4\frac{1}{8}$	$4\frac{3}{16}$
61S-T6	96	$5\frac{1}{4}$	$5\frac{1}{4}$
A17S-T4	84	$5\frac{1}{2}$	$5\frac{5}{16}$
53S-T6	84	$5\frac{5}{8}$	$5\frac{3}{4}$
52S-H12	72	6	6

The author reports:

"The aluminum alloys tested exhibited about the same resistance to permanent set at -120° F as they did at 75° F."

34. Gurtler, G., Jung-Konig, W., and Schmid, E.: Ueber die Dauerbewährung der Leichtmetalle bei verschiedenen Temperaturen. Aluminium, Bd. 21, 1939, pp. 202-208.

Fatigue bending strengths at temperatures as low as -70° C (-94° F) are considered. In referring to articles covered in this summary by items (25), Johnson and Oberg; (28), Boone and Wishart; and (27), Schwinning; the authors say:

> "The data in the literature regarding the behavior at low temperatures are not very clear, but they show that we can not figure on great changes in the fatigue strengths at temperatures down to -70° C [-94° F]."

35. Rosenberg, Samuel J.: Effect of Low Temperatures on the Properties of Aircraft Metals. Res. Paper RP1347, Jour. Res. Nat. Bur. Standards, vol. 25, no. 6, Dec. 1940, pp. 673-701.

Tensile tests were made of nine wrought alloys and four cast alloys at -109° F. These alloys were also tested at room temperature after exposure to -109° F. In addition, Rockwell hardness and Charpy impact tests were made at 32°, -40°, and -109° F.

The wrought alloys were in the form of 0.500-inch plate and the cast alloys in 0.750-inch-diameter bars. Specimens from the plate were tested both transverse and longitudinal to the direction of rolling. A modified specimen was used for impact testing of the wrought alloys. The tensile specimens were $\frac{3}{4}$-inch round specimens, flat on two sides due to thickness of plate, and having $\frac{1}{4}$-inch reduced section. The elongation was measured over 2 inches.

> "The tensile and yield strengths of these materials were but very slightly increased, while the elongation and reduction of area showed no consistent change at -78° C [-109° F]. The results justified the conclusion that there was no significant change in these properties at the low temperature. The modulus of elasticity tended to increase somewhat at -78° C [-109° F]."

> "The tensile properties of specimens taken transversely to the direction of rolling were generally somewhat inferior to those of specimens taken longitudinally with the direction of rolling."

An inspection of the test results will disclose, however, that the tensile properties of the transverse specimens more nearly approach those of the longitudinal specimens at -109° F. This is confirmed by the values of the following table, where the increase of tensile properties at -109° F is consistently greater across grain than with grain.

> "All of the materials increased in hardness as the test temperature decreased. Prolonged exposure at -78° C [-109° F] prior to testing at room temperature had no significant effect upon the hardness of any of these alloys . . . ."

> "The general effect of decreasing test temperatures was either to increase slightly or else not to affect the resistance to impact of these materials. In some cases in which there was an apparent decrease in the impact resistance at certain temperatures, the resistance at -78° C [-109° F] was still not inferior to the impact resistance at room temperature."

The following values have been taken from the plotted data shown in this report:

PERCENT OF INCREASE OR DECREASE IN PROPERTY

AT -109° F OVER ROOM TEMPERATURE

Alloy and temper	Tensile strength		Yield strength		Modulus of elasticity		Elongation in 2 in.		Reduction of area	
	With grain	Across grain	With grain	Across grain	With grain	Across grain	With grain	Across grain	With grain	Across grain
Wrought alloys										
3S-F	21.1	21.1	9.7	10.0	-1.0	5.0	11.7	10.3	2.4	-2.3
17S-T4	3.4	10.3	3.6	4.1	4.9	7.8	9.5	20.0	-10.1	-4.4
17S-T36	4.7	4.7	3.8	5.2	4.8	5.8	-14.3	-7.1	-7.0	-8.3
24S-T4	2.3	3.9	3.1	5.9	11.8	2.9	5.0	-1.7	10.2	-3.8
24S-T36	2.9	4.4	3.6	5.8	7.8	4.8	-4.2	7.1	-16.7	6.5
25S-T6	3.6	3.6	4.2	3.0	4.8	6.6	4.9	5.9	-1.6	3.4
25S-T36	2.6	2.6	2.2	2.4	1.9	7.8	0	9.5	-4.5	21.5
27S-T6	4.1	3.2	1.0	2.4	10.0	7.2	0	4.5	2.7	16.1
52S-F	7.9	6.6	2.3	2.3	-3.2	6.5	31.8	21.0	4.8	4.9
Average	5.8	6.7	3.7	4.6	4.6	6.0	4.9	7.6	-2.2	3.7
Cast alloys										
195-T4	1.5	----	6.2	----	7.8	---	11.1	----	-19.1	----
220-T4	7.1	----	0	----	21.4	---	10.7	----	-10.0	----
335-T4	7.0	----	6.0	----	21.8	---	10.0	----	0	----
356-T4	4.1	----	3.2	----	11.5	---	-20.0	----	11.6	----
Average	4.9	----	3.8	----	15.6	---	3.0	----	-4.4	----

ROCKWELL HARDNESS AND CHARPY IMPACT VALUES OF

WROUGHT ALLOYS AT VARIOUS LOW TEMPERATURES

Alloy and temper	Property	Direction of rolling	Temperature (°F)				
			75	32	-4	-40	-109
3S-F	Rockwell hardness		E-41	E-45	--	E-52	E-56
	Charpy impact, ft-lb	With	36	34	39	36	36
		Across	33	32	34	34	35
17S-T4	Rockwell hardness		B-67	B-68	--	B-68	B-70
	Charpy impact, ft-lb	With	15	15	18	18	18
		Across	9	9	10	10	10
17S-T36	Rockwell hardness		B-74	B-76	--	B-75	B-77
	Charpy impact, ft-lb	With	12	12	13	13	13
		Across	8	8	8	8	9
24S-T4	Rockwell hardness		B-75	B-75	--	B-76	B-77
	Charpy impact, ft-lb	With	12	12	13	13	12
		Across	8	8	8	8	7
24S-T36	Rockwell hardness		B-77	B-79	--	B-80	B-81
	Charpy impact, ft-lb	With	8	9	9	10	9
		Across	5	5	5	5	5
25S-T6	Rockwell hardness		B-65	B-67	--	B-68	B-70
	Charpy impact, ft-lb	With	13	13	15	15	16
		Across	10	10	11	12	11
25S-T36	Rockwell hardness		B-68	B-71	--	B-73	B-74
	Charpy impact, ft-lb	With	11	11	11	11	12
		Across	7	7	8	8	8
27S-T6	Rockwell hardness		B-73	B-74	--	B-75	B-77
	Charpy impact, ft-lb	With	6	6	7	7	8
		Across	5	5	5	5	5
52S-F	Rockwell hardness		E-69	E-70	--	E-71	E-74
	Charpy impact, ft-lb	With	58	57	65	63	57
		Across	25	26	27	27	27

ROCKWELL HARDNESS AND CHARPY IMPACT VALUES OF CAST

ALLOYS AT VARIOUS LOW TEMPERATURES

Alloy and temper	Property	Temperature (°F)				
		75	32	-4	-40	-109
195-T4	Rockwell hardness	E-82	E-85	-	E-82	E-84
	Charpy impact, ft-lb	4	4	5	4	5
220-T4	Rockwell hardness	E-86	E-88	-	E-86	E-85
	Charpy impact, ft-lb	6	6	6	5	3
355-T4	Rockwell hardness	E-83	E-82	-	E-86	E-88
	Charpy impact, ft-lb	2	2	2	2	2
356-T4	Rockwell hardness	E-66	E-66	-	E-68	E-71
	Charpy impact, ft-lb	2	2	2	2	2

36. Gillett, H. W.: Impact Resistance and Tensile Properties of Metals at Subatmospheric Temperatures. A.S.T.M., Aug. 1941.

This article summarizes data, both published and unpublished, from numerous sources. Most of these sources have already been covered in this summary by items (12), Güldner; (18), Russell; (20), Matthaes; (25), Johnson and Oberg; (24), Colbeck and MacGillivray; and (35), Rosenberg.

The values not already included in this summary are as follows:

Property	Temperature (°F)	Sand-cast alloy (a)	Sand-cast 355-T7	Forged 25S-T6
Tensile strength, psi	Room -40	33,000 33,500	43,500 43,000	60,500 66,000
Yield strength, psi	Room -40	------- -------	------- -------	34,500 40,000
Elongation, percent	Room -40	------- -------	------- -------	21.0 17.5
Reduction of area, percent	Room -40	------- -------	------- -------	27 31
Brinell hardness	Room -40	75 74	------- -------	113 112
Endurance limit (unnotched bars), psi	Room -40	[b]10,000 [b]11,000	[c]8,000 [c]10,000	[d]15,000 [d]18,000

[a]1.29 percent Si, 1.02 percent Fe, 4.26 percent Cu; aged 2 hr at 300° F.
[b]Tests run to 500,000,000 cycles.
[c]Tests run to 100,000,000 cycles.
[d]Tests run to 500,000,000 cycles. (100 million cycles on 0.30-in.-diameter bars with V-notches 0.015 and 0.038 in. deep, 0.003-in. radius, at room temperature and -40° F. All four tests gave 8000 psi.)

In commenting about the test values from the various sources, the author says:

"All these non-ferrous alloys are shown to have very closely the same properties at -40° F as at room temperature."

"No deterioration in properties is met at -105° F in these wrought alloys.[4]"

"Except for the impact value of No. 27 [220-T4] at -105° F, the determinations [of casting alloys] at -105° F could be taken as checking the room temperature figures.[4]"

[4]"Effect of Low Temperatures on the Properties of Aircraft Metals" by Samuel J. Rosenberg. See item (35) of this summary.

37. Irmann, R.: Einfluss einer Erwärmung auf die Festigkeitseigenschaften von Reinaluminium und Aluminium-Knetlegierungen. Aluminium, Bd. 23, Nov. 1941, pp. 530-540.

The author shows results of tensile, fatigue, and impact tests at temperatures as low as -112° F. The graphs of this report show that these properties increase as the temperature decreases. At -112° F they all show increases in the order of 10 percent over corresponding properties at room temperature.

38. White, A. E., and Siebert, C. A.: Report on Literature Survey on the Low Temperature Properties of Metals to October 1941. OSRD Rep. No. 281, Dec. 1941.

The authors have collected data from sources covered in this summary by items (10), Strauss; (13), Musatti; (24), Colbeck and MacGillivray; (26), DeHaas and Hadfield; (28), Boone and Wishart; and (35), Rosenberg.

39. Anon.: Mechanical Properties of Alloys at Low Temperatures. Light Metals, vol. IV, Jan. 1941 to Jan. 1942, pp. 212-215.

This is a commentary on the results of tests made of aluminum and magnesium alloys as reported previously by others and covered in this summary by items (24), Colbeck and MacGillivray; (20), Matthaes; (22), Bollenrath; and (35), Rosenberg.

The data of these reports are interpreted to indicate that:

(1) ". . . tensile and yield strengths increase only slightly, whilst elongation and reduction of area show no consistent change at -78° C [-108° F]. Modulus of elasticity tended to increase at this temperature."

(2) "Regarding the impact tests . . ., the general effect of reduced temperature was either slightly to increase resistance to impact or not to affect it at all."

40. Gurtler, G., and Jung-Konig, W.: Warmfestigkeit von Aluminium-Gusslegierungen. Aluminium, Bd. 24, Nr. 5, May 1942, pp. 166-169.

Tensile tests of two cast aluminum alloys were made at low temperatures. The following values are shown in graphical form:

Alloy and temper	Temperature (°F)	Tensile strength (psi)	Elongation (percent)
G Al-Si-Mg, age-hardened	68	42,000	1.0
	-148	44,800	1.0
	-300	49,800	.5
G Al-Si, as-cast	68	27,000	6.5
	-148	32,700	6.0
	-300	37,700	4.0

The authors make the following comments:

"At low temperatures, yield strength, tensile strength and hardness increase with slight reduction in elongation, while the notch toughness remains unchanged."

"The very few data on fatigue strength in the literature indicate an increase in this property with decreasing temperature, just like the wrought alloys."

41. McAdam, D. J., Jr., and Mebs, R. W.: The Technical Cohesive Strength and Other Mechanical Properties of Metals at Low Temperatures. Proc. A.S.T.M., vol. 43, 1943, pp. 661-706.

The authors have presented data on technical cohesive strength at room temperature and selected low temperatures, and used it as a basis for interpretation of the influence of low temperature on the strength, ductility, and total work of notched and unnotched specimens. Among other metals and alloys, the authors tested aluminum of 99.97 percent purity and aluminum of 99.4 percent purity in the form of cold-drawn rods.

The following tensile strengths are shown:

Temperature (°F)	Tensile strength (psi)	
	99.97 percent Al	99.4 percent Al
Room	17,000	22,000
-18	18,000	------
-112	19,000	------
-166	21,000	26,000
-306	26,000	33,000

42. Everhart, John L., Lindlief, W. Earl, Kanegis, James, Weissler, Pearl G., and Siegel, Frieda: Mechanical Properties of Metals and Alloys. Circular C447, Nat. Bur. of Standards. U.S. Govt. Printing Office, Dec. 1943.

The data pertinent to this subject were collected by the authors from sources covered by items (18), Russell; (21), Sandell; (24), Colbeck and MacGillivray; (26), DeHaas and Hadfield; (32), Bungardt; and (36), Gillett.

43. McAdam, D. J., Jr., Mebs, R. W., and Geil, G. W.: The Technical Cohesive Strength of Some Steels and Light Alloys at Low Temperatures. Proc. A.S.T.M., vol. 44, 1944, pp. 593-624.

The authors tested $\frac{3}{4}$-inch diameter 24S-T4 rod and also similar rod reduced about 13 percent in cross section by cold-drawing. Results of their tensile tests are as follows:

Alloy and temper	Property (psi)	Room temperature	-4° F	-108° F	-184° F	-306° F
24S-T4	Tensile strength	69,000	71,000	72,000	76,000	85,000
	Yield strength	45,000	44,000	46,000	49,000	57,000
24S-T4, cold-drawn 13 percent	Tensile strength	80,000	81,000	82,000	85,000	95,000
	Yield strength	74,000	74,000	76,000	79,000	88,000

44. Donaldson, J. W.: Properties of Metals and Alloys at Sub-Zero Temperatures. Metal Treatment, vol. XI, no. 39, Autumn 1944, pp. 161-170.

The author reviews articles written by several investigators on this subject. Most of the articles deal with ferrous alloys. The section dealing with aluminum is a review of the article covered by item (35), Rosenberg, of this summary. Concerning this article, the author says:

"The tensile properties and the hardness of all materials were generally improved at low temperatures."

45. Petty, Paul Beal: Memorandum on Subzero Application for Aluminum. Hydrocarbon Research, Inc. (New York City), Oct. 5, 1944.

Duplicate notched specimens were tested by two separate laboratories and results from both are listed as follows:

Results of tests made by the Crane Company:

Alloy and temper	Charpy keyhole-notch impact values, ft-lb, at -	
	80° F	-300° F
3S-H12	13.5	12.8
61S-T6	5.5	5.2

Results of tests made by the Standard Oil Development Company:

Alloy and temper	Impact values, ft-lb, at -				
	Room temperature	-240° F	-260° F	-300° F	-320° F
3S-H12	17	23	23	22	22
53S-T6	9	9	8	9	9
61S-T6	10	11	11	10	10
195-T6	2	2	2	2	2
356-T6	1	1	1	1	1

On comparing the results of tests at the Crane Company with those at the Standard Oil Development Company, two points are emphasized:

(1) "Results from different heats of the same alloy may show different impact values."

(2) "Impact values should be studied through the complete temperature range that is under consideration without special regard to numerical values. Too much attention has been given to meeting certain values."

"The values herein from Crane Co., when compared to SOD data attached, show the same trend. If the impact values are good enough at room temperature, it is reasonable to predict that they would be satisfactory to -320° F."

46. Petty, Paul Beal: Metals for Service at Sub-Zero Temperatures. Hydrocarbon Research, Inc., Chemical and Metallurgical Eng., vol. 52, June 1945, pp. 102-103.

The following Izod values are shown in this report for rolled and annealed aluminum (alloy not stated):

Temperature (°F)	Izod impact (ft-lb)
69	19
-42	19
-112	20
-185	21
-295	27

The author states:

"For all practical purposes the physical properties of aluminum at subzero temperatures remain unchanged or actually improve."

47. Maney, G. A., and Wyly, L. T.: Impact Properties at Different Temperatures of Flush-Riveted Joints for Aircraft Manufactured by Various Riveting Methods. NACA ARR 5F07, 1945.

Tests of riveted joints were made on a pendulum impact machine at temperatures of 70°, -50°, and -70° F. The materials were in the form of $\frac{3}{32}$-inch rivets of A17S-T4 joining 0.064-inch-thick sheets of 24S-T4.

The following test results are given for the four different methods of riveting:

Method of riveting	Temperature (°F)	Energy (ft-lb)
h_b[1] = -0.003	70	0.50, 0.60, 0.60, 0.75, 0.80
	-52	1.10
	-57	1.00
	-66	1.00
	-67	1.00, 1.03
h_b[1] = 0.000	70	.55, .60, .60, .60, .65
	-56	1.00, 1.20
	-66	1.00, 1.00
	-70	.95
h_b[1] = 0.010	70	.40, .40, .45, .50, .50
	-53	.80
	-55	.90
	-67	.90
	-70	.95, .95
E[2]	70	.30, .40, .40, .40, .45
	-53	.80
	-55	.90
	-70	.90
	-71	.80, .85

[1]h_b is the height of the center of the rivet head above the surface of the sheet before the rivet is driven. The manufactured head of the countersunk rivet is driven with a vibrating gun, while the shank end is bucked with a bar. The driven rivet head is flat.

[2]Method E: The manufactured round head of the rivet is driven with a vibrating gun, while the shank end is bucked with a bar. After the rivet is driven, the portion of the formed head that protrudes above the skin surface is milled off and finished smooth with the sheet.

The authors say:

"The most outstanding result of these tests was the remarkable increase in impact strength noted at low temperatures."

". . . all available information regarding the variation of the coefficient of thermal expansion between the plate and the rivet materials indicated no substantial effect on clamping force from temperature change."

"There is no reason to believe that the stress distribution in the specimens of this series tested at low temperature differs from that in the specimens tested at room temperature."

Torsion impact tests of 17S-T4 at 70° and -70° F were also made. These tests were made on a Carpenter torsion impact machine.

The following test results are given:

Temperature (°F)	Energy of rupture (ft-lb)	Modulus of toughness
70	53.69	1085
-70	61.88	1192

"It will be noted that the strength in torsion impact at -70° F is about 10 percent greater than at 70° F, a result consistent with information obtained by other investigators but throwing no light on the much greater impact strengths found at low temperatures in the joints tested herein. In short, this investigation indicated that the increased impact strength of the joints was not solely due to testing at low temperatures."

Photomicrographs showed no great differentiation with temperature between the microconstituents.

Tests of joints were also made. Each specimen consisted of two flat 24S-T4 plates 1 inch wide and $\frac{1}{8}$ inch thick riveted together with two $\frac{1}{8}$-inch-diameter rivets of 17S-T4.

The tests were made at 70° F, at -70° F, and at 70° F after being held for 28 hours at -70° F.

"Considerable increase in impact strength was found for all joints which had been subjected to the low temperature treatment, and this held for the specimens which had been at 70° F for 28 hours after removal from the low temperature chamber. In no case, however, was this increase in strength nearly so large as that shown by the main test series, although the increase was larger than that reported in references 1, 2, and 7. [See items (25), Johnson and Oberg; (17), Templin and Paul; and (35), Rosenberg.] Also the variation in the results was much greater than in the case of the main test series."

As a general conclusion, the authors state:

"The strength of the rivet stock tested is increased from 60 to 120 percent when tested at temperatures as low as -50° F."

48. Jackson, L. R., Grover, H. J., and McMaster, R. C.: Advisory Report on Fatigue Properties of Aircraft Materials and Structures. OSRD No. 6600, Serial No. M-653, War Metallurgy Div., NDRC, March 1, 1946.

In reviewing the available information on aircraft materials and structures under repeated load, the authors touch lightly upon the effects of low temperatures on fatigue strength. Referring to articles reviewed in items (34), Gurtler, Jung-Konig, and Schmid; (25), Johnson and Oberg; and (28), Boone and Wishart; the authors say:

"These results and results in other references suggest that fatigue strengths of aluminum alloys are not lowered by low temperatures."

49. Kostenetz, V. I.: Mechanical Properties of Metals and Alloys in Tension at Low Temperatures. Jour. Tech. Phys. (U.S.S.R.), vol. 16, no. 5, 1946, pp. 515-554. (As reviewed by Metal Progress, vol. 55, no. 1, Jan. 1949, p. 82.)

Tensile tests were made at 63°, -321°, and -424° F.

"The tests were made in a vacuum bottle containing about three pints of liquefied nitrogen or hydrogen surrounding the specimen at the start of each test. Loads up to 3000 lb were applied by means of a piston and a cylinder containing oil. The specimens had a gage length of 30 mm and a diameter of 3 mm. The elongation of the specimens was measured with a cathetometer, through a longitudinal window in the metal vacuum bottle. Each test required about 15 min."

"The face-centered cubic metals, which include aluminum, increase in both strength and ductility as the temperature of testing is lowered."

"Although the tensile strength of each face-centered cubic alloy increased as the test temperature was decreased, the percentage increase was less than for the pure metals. Generally the elongation increased and the reduction of area remained about the same or decreased as the temperature was lowered. The face-centered cubic alloys remained ductile down to -424° F, but the cast aluminum-silicon and magnesium-aluminum alloys were brittle at all test temperatures."

The following test results are given:

Metal or alloy	Composition (percent)	Temperature (°F)	Tensile strength (psi)	Elongation (percent)	Reduction of area (percent)
Aluminum (rod)	Al 99.7	63	17,000	29	86
		-321	30,000	42	75
		-424	50,000	45	66
Duralumin (17S)	4.2 percent Cu,	633	58,000	15	25
	0.6 percent Mg,	-321	74,000	16	20
	0.6 percent Mn	-424	97,000	16	16
Lautal (25S)	4.3 percent Cu,	63	31,000	7	14
	0.8 percent Mn,	-321	45,000	9	11
	0.9 percent Si	-424	60,000	12	13
Silumin (cast)	10.0 percent Si	63	18,000	1.2	.6
		-321	18,000	.8	0
		-424	33,000	1.4	1.5

50. Anon.: Properties of Various Alloys at Sub-Zero Temperatures. The Iron Age, vol. 158, Nov. 14, 1946, p. 75.

The following results of tensile tests are given:

Alloy and temper	Room temperature			-320° F		
	Ultimate strength (psi)	Yield strength (psi)	Elongation in 2 in. (percent)	Ultimate strength (psi)	Yield strength (psi)	Elongation in 2 in. (percent)
Alclad 75S-T6	78,100	67,100	11.0	91,900	79,800	6.0
52S-0	28,100	14,100	19.5	42,300	16,600	23.5
Alclad 24S-T4	68,700	47,000	20.0	85,000	59,400	14.5

Tests were also made of welded specimens. The results of these tests follow:

Alloy and temper	Room temperature		-320° F	
	Ultimate strength (psi)	Joint efficiency (1)	Ultimate strength (psi)	Joint efficiency (1)
Alclad 75S-T6, seam weld[2]	37,900	48.5	29,700	32.4

[1]Joint efficiency, ratio in percent of weld ultimate strength to parent metal ultimate at test temperature.
[2]Fractured in weld.

The following comments are made:

"An investigation to determine the mechanical properties of various ferrous and non-ferrous alloys at -320° F, conducted by the engineering research laboratory of North American Aviation, Inc., Inglewood, Calif., indicated that both tensile and yield strength of all alloys tested are greater at the sub-zero temperature than at room temperature."

". . . the . . . aluminum alloys still retained sufficient ductility at -320° F to permit their use for general structural application . . . . In general, the joint efficiency of resistance seam . . . welded joints of all the alloys tested was lower at -320° F than at room temperature."

Of all the alloys tested, the only ones that showed lower strengths at -320° F were those which fractured in the weld. No statement was made concerning soundness of the welds.

51. McAdam, D. J., Jr., Geil, G. W., and Mebs, R. W.: Effects of Combined Stresses and Low Temperatures on the Mechanical Properties of Some Non-Ferrous Metals. Trans. Am. Soc. Metals, vol. 37, 1946, pp. 497-537.

An investigation was made of various metals and alloys including commercial aluminum and high-purity aluminum to find the influence of notches and of the stress system on resistance to plastic deformation, resistance to fracture, and ductility between room temperature and -306° F.

In reference to ductility, the authors state:

"Aluminum evidently increases in ductility with decrease of temperature."

The following results of tensile tests of unnotched specimens are shown:

Alloy	Property (psi)	Room temperature	-4° F	-108° F	-184° F	-306° F
99.97 percent Al	Tensile strength	18,000	18,500	19,000	21,500	26,500
	Yield strength	17,000	------	18,000	------	20,500
99.4 percent Al	Tensile strength	22,000	------	25,000	26,500	33,000
	Yield strength	21,000	------	23,000	------	26,500

52. Klinger, R. F.: Effect of Low Temperatures on Extruded Aluminum Alloys. Wright Field Rep. No. T-SEAM-M5197, March 14, 1947. (As taken from "An Appraisal of the Usefulness of Aluminum Alloys for Supersonic Aircraft and Guided Missile Construction," by C. M. Craighead, L. W. Eastwood, and C. H. Lorig, Project RAND, Battelle Memorial Inst., R-104, Aug. 8, 1948, p. 41.)

Tests were made to determine tensile and yield strengths, elongation, reduction of area, and Izod impact strengths of 14S-T6, 24S-T4, 75S-T6, and R-303-T275 extrusions at -67° and -100° F.

Tests were also made at room temperature after 24 hours of exposure to the low temperatures. These latter show no change in property due to exposure to the low temperatures.

The following test results are given:

Alloy and temper	Temperature (°F)	Tensile strength (psi)	Yield strength (psi)	Elongation (percent)	Izod impact values (ft-lb)
14S-T6	Room	77,700	66,500	10.0	----
	-67	80,800	66,400	10.1	----
	-100	80,300	71,400	9.7	----
24S-T4	Room	84,100	63,400	14.1	13.4
	-67	87,000	66,400	13.8	13.3
	-100	86,000	67,100	13.7	13.8
75S-T6	Room	86,100	76,400	10.7	7.3
	-67	92,800	85,500	9.8	6.0
	-100	93,200	85,100	9.7	6.2
R303-T275	Room	88,700	84,900	7.2	----
	-67	94,600	91,600	7.4	----
	-100	95,000	91,200	5.9	----

53. Schmitt, Phillip: Low-Temperature Fatigue Properties of 75S-T Extruded Aluminum Alloy. Wright Field Rep. No. T-SEAM-M5197, Add. 1, March 27, 1947.
(As taken from "An Appraisal of the Usefulness of Aluminum Alloys for Supersonic Aircraft and Guided Missile Construction," by C. M. Craighead, L. W. Eastwood, and C. H. Lorig. Project RAND, Battelle Memorial Inst., R-104, Aug. 8, 1948, p. 61.)

Various tensile and rotating-beam fatigue tests were made of 75S-T6 extrusions at room temperature and -70° F. The following results are given:

Testing temperature (°F)	Direction	Tensile strength (psi)	Yield strength (psi)	Elongation in 4 diameters (percent)	Fatigue strength (max. stress) at 200,000,000 cycles (psi)
Room	L	86,000	78,000	10.0	18,500
-70	L	94,000	88,000	9.0	22,500
Room	V - T[1]	70,100	63,700	3.0	16,000
-70	V - T[1]	65,500	61,500	2.0	14,000

[1]Vertical to base and transverse to length.

54. Druyvesteyn, M. J.: Experiments on the Effect of Low Temperature on Some Plastic Properties of Metals. Appl. Sci. Res., no. A1, 1947, pp. 66-80.
(As taken from Chemical Abstracts, vol. 42, no. 10, May 20, 1948, p. 3297.)

"The temp. coeffs., of some plastic properties of metals were measured in an attempt to avoid the difficulties involved in a direct comparison of the properties themselves because of unavoidable variations in grain size, annealing, velocity of measurement, and dimensions of the test bar. The yield values, breaking strengths, hardness, and elongation at -183° [-297° F], at room temp., and in a few cases at higher temps. were measured."

"The increase is small for face-centered metals."

"The breaking strength and hardness generally increase with decreasing temp."

"For cubic face-centered metals the increase in hardness increases with decreasing m.p. The effect of temp. on the elongation is very different for different metals. In general, metals having smaller temp. coeffs. of yield point have larger elongations at lower temps."

55. Howell, F. M., and Stickley, G. W.: The Mechanical Properties of Alcoa Wrought Aluminum Alloy Products at Various Temperatures. Aluminum Co. of Am., Aluminum Res. Laboratories, Rep. No. 9-47-9, Dec. 12, 1947.

The following typical tensile values are given:

Alloy and temper	Product and size	Temperature (°F)	Tensile strength (psi)	Yield strength (psi) (1)	Elongation in 4 diameters (percent)
2S-0	All	75	13,000	5,000	45
		0	13,500	5,000	46
		-112	15,000	5,000	50
		-320	24,500	6,000	57
2S-H14	All	75	17,500	16,000	20
		0	18,000	16,000	20
		-112	19,500	17,000	23
		-320	28,500	19,000	42
2S-H18	All	75	24,000	22,000	15
		0	25,000	22,500	15
		-112	26,000	23,000	17
		-320	35,500	26,500	35
3S-0	All	75	16,000	6,000	40
		0	17,000	6,000	41
		-112	19,500	7,000	42
		-320	33,000	8,500	46
3S-H14	All	75	21,500	19,000	16
		0	22,500	19,500	16
		-112	24,500	20,000	18
		-320	36,000	23,500	30
3S-H18	All	75	29,000	26,000	10
		0	30,500	26,500	10
		-112	32,000	28,000	11
		-320	42,500	32,000	27
14S-T4	Extrusions, 0.125 to 0.749 in.	75	62,000	44,000	--
		0	64,000	44,000	--
		-112	65,000	45,000	--
		-320	81,000	60,000	--
14S-T4	Extrusions, 0.750 in. or more	75	70,000	49,000	16
		0	72,000	49,000	16
		-112	73,000	50,000	16
		-320	91,000	67,000	16
14S-T6	Alclad sheet, 0.020 to 0.039 in.	75	65,000	58,000	--
		0	65,000	58,000	--
		-112	66,000	59,000	--
		-320	76,000	65,000	--
14S-T6	Alclad sheet, 0.040 to 1.000 in.	75	68,000	60,000	--
		0	68,000	60,000	--
		-112	70,000	61,000	--
		-320	80,000	68,000	--
14S-T6	Forgings and rolled shapes	75	70,000	60,000	13
		0	70,000	60,000	13
		-112	72,000	61,000	14
		-320	82,000	68,000	14
14S-T6	Extrusions, 0.125 to 0.499 in.	75	68,000	62,000	--
		0	69,000	63,000	--
		-112	71,000	65,000	--
		-320	84,000	77,000	--
14S-T6	Extrusions, 0.500 to 0.749 in.	75	73,000	67,000	--
		0	75,000	68,000	--
		-112	77,000	70,000	--
		-320	91,000	84,000	--
14S-T6	Extrusions, 0.750 in., or more[2]	75	75,000	69,000	11
		0	77,000	70,000	11
		-112	79,000	72,000	11
		-320	93,000	86,000	11
24S-T3, 24S-T4	Wire, rod, and bar	75	68,000	46,000	22
		0	70,000	47,000	23
		-112	72,000	49,000	24
		-320	86,000	61,000	25
24S-T3, 24S-T4	Alclad sheet, 0.012 to 0.063 in.	75	64,000	43,000	--
		0	66,000	44,000	--
		-112	68,000	46,000	--
		-320	81,000	57,000	--
24S-T3, 24S-T4	Alclad sheet and plate, 0.064 to 0.500 in.	75	66,000	44,000	--
		0	68,000	45,000	--
		-112	70,000	47,000	--
		-320	84,000	58,000	--
24S-T3	Tubing	75	72,000	50,000	--
		0	74,000	51,000	--
		-112	76,000	53,000	--
		-320	91,000	66,000	--
24S-T4	Extrusions, less than 0.250 in.	75	63,000	50,000	--
		0	63,000	50,000	--
		-112	64,000	52,000	--
		-320	81,000	68,000	--
24S-T4	Extrusions, 0.250 to 0.749 in.	75	69,000	54,000	--
		0	69,000	54,000	--
		-112	71,000	56,000	--
		-320	88,000	73,000	--
24S-T4	Extrusions, 0.750 in. or more	75	78,000	58,000	13
		0	78,000	58,000	13
		-112	80,000	61,000	13
		-320	100,000	78,000	11
53S-0	All	75	16,000	7,000	35
		0	17,000	7,500	37
		-112	19,000	8,500	39
		-320	33,000	10,000	53
53S-T4	All	75	33,000	20,000	30
		0	34,000	21,000	31
		-112	36,000	21,000	32
		-320	48,000	27,000	38
53S-T6	All	75	39,000	33,000	20
		0	41,000	34,000	21
		-112	44,000	36,000	22
		-320	56,000	42,000	30
61S-0	All	75	18,000	8,000	30
		0	19,000	8,500	32
		-112	20,000	9,000	36
		-320	34,000	11,000	45
61S-T4	All	75	35,000	21,000	25
		0	36,000	22,000	26
		-112	38,000	22,000	27
		-320	50,000	28,000	31
61S-T6	All	75	45,000	40,000	17
		0	47,000	41,000	17
		-112	49,000	42,000	18
		-320	60,000	47,000	22
75S-0	Sheet, plate, wire, rod, and bar	75	34,000	15,000	16
		0	35,000	15,000	16
		-112	37,000	16,000	18
		-320	50,000	19,000	20
75S-0	Alclad sheet and plate	75	32,000	14,000	--
		0	33,000	14,000	--
		-112	35,000	15,000	--
		-320	47,000	18,000	--
75S-T6	Sheet, plate, wire, rod,[3] and bar	75	82,000	72,000	11
		0	83,000	73,000	11
		-112	86,000	75,000	11
		-320	98,000	85,000	12
75S-T6	Alclad sheet and plate (max. thickness, 2 in.)	75	76,000	67,000	--
		0	77,000	68,000	--
		-112	80,000	70,000	--
		-320	91,000	79,000	--
75S-T6	Extrusions[4]	75	88,000	80,000	10
		0	91,000	82,000	9
		-112	93,000	85,000	8
		-320	112,000	104,000	7

[1]Offset, 0.2 percent.
[2]Maximum cross-sectional area, 25 sq in.
[3]Maximum thickness, 2 in.
[4]Maximum thickness, 4 in.; maximum cross-sectional area, 20 sq in.

The following typical values of modulus of elasticity are listed:

Temperature (^{o}F)	Approximate percentage of increase at low temperatures
-18	2
-112	7
-320	12

The typical values shown in these tables are based on tests which are included among those listed in item (61)

56. Franks, Russell: Properties of Metals at Low Temperature. Metals Handbook, Am. Soc. Metals, 1948, pp. 204-215.

This article presents data collected from various sources. Part of it has already been covered in this summary by items (17), Templin and Paul; (24), Colbeck and MacGillivray; and (35), Rosenberg.

In addition to this the following table of temperature coefficients of the elastic modulus of aluminum alloys is given. These values were taken from "The Modulus of Elasticity of Light Alloys and Its Change with the Temperature," by J. Chailloux. Publications Scientifiques et Techniques No. 122, Ministère de l'Air (Paris), 1938.

Composition	Temper	Temperature range (^{o}C)	Temperature coefficient, e (1)
4.0 percent Cu, 1.2 percent Mg, 1.2 percent Mn	Quenched	-50 to 70 -190 to -48	32×10^{-5} 46
1.9 percent Cu, 0.8 percent Mg, 1.2 percent Ni, 1.4 percent Fe, 0.1 percent Ti, 0.6 percent Si	Age-hardened	-56 to 68 -190 to -56	31 53
2.5 percent Cu, 0.7 percent Mg, 1.2 percent Ni, 0.9 percent Si, 1.0 percent Fe, 0.1 percent Ce	Age-hardened	20 to -44 -190 to -44	28 57
1.1 percent Cu, 0.01 percent Mg, 0.1 percent Mn, 1.5 percent Si, 0.8 percent Fe	Quenched	20 to -70 -190 to -70	34 62
9.5 percent Mg, 0.35 percent Mn, 0.10 percent Si, 0.20 percent Fe	Annealed	20 to -41 -190 to -41	13 37
1.10 percent Mg, 0.01 percent Mn, 0.7 percent Si, 0.28 percent Fe	Quenched	0 to 50 -190 to -50	29 48

[1] $e = \frac{1}{E} \cdot \frac{dE}{dT}$.

The following hitherto unpublished data from tensile tests at low temperatures are included:

Alloy and temper	Composition	Temperature (°F)	Tensile strength (psi)	Yield strength (psi)	Elongation in 2 in. (percent)
3S-H12	1.2 percent Mn	75 -18 -112	19,900 21,200 23,300	18,300 18,800 19,700	24.0 24.0 28.0
18S-T61	4.0 percent Cu, 0.5 percent Mg, 2.0 percent Ni	75 -112	66,500 68,900	54,800 56,000	12.3 14.0
24S-T4	4.5 percent Cu, 1.5 percent Mg, 0.6 percent Mn	75 -112	70,100 74,100	43,700 46,400	23.3 25.3
25S-0	4.5 percent Cu, 0.8 percent Mn, 0.8 percent Si	75 -112	28,100 29,500	19,000 ------	15.0 18.0
52S-H32	2.5 percent Zn, 0.25 percent Cr	75 -112	35,000 36,700	29,300 29,300	19.5 23.0
61S-T6	0.25 percent Cu, 1.0 percent Mg, 0.6 percent Si, 0.25 percent Cr	75 -112	46,000 50,400	39,200 41,700	21.0 22.5
75S-T6	1.6 percent Cu, 2.5 percent Mg, 0.2 percent Mn, 5.6 percent Zn, 0.3 percent Cr	75 -112	81,300 85,400	70,300 73,300	15.0 15.3
112, as-cast	7.0 percent Cu, 1.7 percent Zn	75 -112	26,100 28,200	20,900 22,500	.8 1.0
122, as-cast	10.0 percent Cu 0.2 percent Mg	75 -112	30,100 28,900	27,000 27,500	.2 0
142-T61	4.0 percent Cu, 1.5 percent Mg, 2.0 percent Ni	75 -112	37,000 42,500	------ ------	0 0

Concerning these data the author states:

". . . concerning the toughness and tensile strength of the different aluminum alloys, the data indicate that neither the strength nor the ductility of the various aluminum alloys changes greatly when subjected to temperatures as low as minus 112° F. In fact, the indications are that the ductility of the aluminum is increased slightly as a result of exposure to low temperature. It is apparent that cold rolling the aluminum alloys does not affect the ductility at low temperature, which means that aluminum and aluminum alloys have a high degree of structural stability when exposed under such conditions."

57. Seigle, L., and Brick, R. M.: Mechanical Properties of Metals at Low Temperatures; A Survey. Trans. Am. Soc. Metals, vol. 40, 1948, pp. 813-869.

The authors have made a study of the ductility of various metals at -301° F. As a result of their investigation the authors state that:

"Only face-centered cubic metals [including aluminum] retain their ductility as the deformation temperature approaches absolute zero."

58. Craighead, C. M., Eastwood, L. W., and Lorig, C. H.: An Appraisal of the Usefulness of Aluminum Alloys for Supersonic Aircraft and Guided Missile Construction. Project RAND, Battelle Memorial Inst., R-104, Aug. 8, 1948.

A very comprehensive review of all available data on mechanical properties of aluminum at various temperatures has been prepared by the authors. They have collected data from sources covered in this summary by items (55), Howell and Stickley; (60), Fontana and Zambrow; (17), Templin and Paul; (42), Everhart, Lindlief, Kanegis, Weissler, and Siegel; and (52), Klinger.

Additional data of an unpublished nature from Battelle Memorial Institute have been included. These are results of tests of 2-inch-thick 3S welded plate at room temperature, -327°, and -420° F. Results of these tests are as follows:

Alloy	Direction	Temperature (°F)	Tensile strength (psi)	Yield strength (psi) (1)	Elongation in 2 in. (percent)	Impact value (ft-lb) (2)
3S	T	Room	16,000	8,600	36	16
		-327	33,500	12,000	41	16
		Room	16,800	------	24	16
		-420	43,100	------	26	16.8

[1]Offset, 0.2 percent.
[2]Charpy impact bar with keyhole notch.

Filler metal (1)	Welding process	Temper-ature (°F)	Tensile strength (psi)	Yield strength (psi) (2)	Elongation in 2 in. (percent)	Impact value (ft-lb) (3)
2S	Argon arc	Room	15,700	5,000	33	11.0
		-327	------	------	--	13.0
		Room	15,300	------	32	11.0
		-420	42,800	------	26	12.7
2S	Carbon arc	Room	16,000	8,500	28	9.5
		-327	31,000	8,800	31	13.0
		Room	15,200	------	22	9.5
		-420	38,500	------	30	11.6
2S	Carbon and argon arc	Room	15,800	8,100	17	----
		-327	32,900	10,500	31	----
43S	Argon arc	Room	23,000	7,300	21	3.2
		-327	------	------	--	2.2

[1]0.505-in.-diameter all-weld metal bars.
[2]Offset, 0.2 percent.
[3]Charpy impact bar with keyhole notch.

59. Wellinger, Karl, and Hofmann, Artur: Prüfung Metallischer Werkstoffe in der Kalte. Zeitschr. für Metallkunde, Bd. 39, 1948, p. 233. (Abstracted in article "Low-Temperature Properties of Al." Metal Progress, vol. 55, no. 4, April 1949, pp. 526, 528.)

The authors made tests of high-purity aluminum (0.11 percent Si) and two aluminum alloys, one containing 2.8 percent Mg and 0.37 percent Mn, the other 2.29 percent Mg and 2.04 percent Mn.

Tensile tests were made at 68°, -76°, and -297° F. Fatigue tests were run at 68°, -67°, -102°, and (for pure aluminum) -256° F.

Tensile data included: (1) Yield strength, (2) true stress and actual strain up to the point where necking started, and (3) ultimate tensile strength, final deformations, and true stress to fracture. The latter was determined in tension-impact tests on notched specimens.

They found that low temperature has slight effect on the yield strength of aluminum or either of the two alloys tested, down to -76° F, but at -297° F the yield strength rises rapidly.

In the case of pure aluminum, the reduction of area remains constant whereas other tensile properties increase as the temperature decreases.

The 3-percent-Mg alloy showed increases in strength characteristics at an accelerated rate as temperatures decreased. Final reduction of area, however, increases to -76° F and then decreases to -297° F. Diagrams in the original article, however, show that it is still equal to the reduction of area at room temperature.

Reference to the original article will also show that all tensile properties of the Al-Mg-Mn alloy increased at the low temperatures with the exception of reduction of area which was 21 percent at room temperature, slightly higher at -76° F, and about 17.5 percent at -297° F.

The fatigue limit of the two alloys is increased but only to the extent of about 10 percent (13,000 to 14,000 psi) between 68° and -102° F. For the pure aluminum, the fatigue limit is about the same at temperatures down to -256° F, any slight change being in the nature of an increase.

A variation in apparatus for low-temperature testing was used and is described in the article.

The authors theorize concerning causes for changes in tensile properties at the low temperatures.

60. Zambrow, J. L., and Fontana, M. G.: Mechanical Properties, Including Fatigue, of Aircraft Alloys at Very Low Temperatures. Trans. Am. Soc. Metals, vol. XLI, 1949, pp. 480-518.

An extensive program of tests at subzero temperatures is reported. Fatigue, impact, hardness, and tensile tests were made of 2S-H16, 24S-T4, 61S-T6, and 75S-T6. In addition to this, compressive tests were made of 24S-T4 and 61S-T6.

The fatigue tests were made at -108° and -321° F. The Charpy impact tests were made at -108°, -197°, -314°, and -423° F. Vickers hardness, tensile, and compressive tests were made at -108° and -314° F.

In the authors' closure to the discussion following the paper, they present the test results in table form. These tables summarize the data which were obtained in the investigation and include many results which were obtained after the paper was submitted for publication. The Charpy impact values at -196° F, and certain fatigue strengths at room temperature, are taken from graphical representations in the paper itself. All other values shown in the following table are taken from the closure.

Concerning these results, the authors say:

"There appeared to be a good correlation between the ultimate tensile strength and the fatigue strength at high stress levels. For example, the aluminum alloys showed only a slight increase in tensile strength between room temperature and -78° C [-108° F] and there was likewise only a small increase in the fatigue strength. Between -78° C [-108° F] and -196° C [-321° F] there was a comparatively large increase in tensile strength and a correspondingly large increase in the fatigue strength."

"The 2S aluminum showed an increase [in impact values with falling temperature]; and the values for the remaining aluminum alloys . . . remained fairly constant over the range of test temperatures."

Alloy and temper	Temperature (°F)	Tensile strength (psi)	Tensile yield strength (psi)	Elongation (percent)	Reduction of area (percent)	Compressive yield strength (psi)	Modulus of elasticity (psi)		Vickers hardness number	Fatigue strength, psi, at -			Charpy impact value (ft-lb)
							Tension	Compression		10^6 cycles	10^7 cycles	10^8 cycles	
2S-H16	77	19,500	17,500	24.0	80.5	------	10.05×10^{-6}	------------	43.5	13,000	11,000	------	28.0
	-108	21,600	18,200	26.5	77.0	------	11.25	------------	49.7	------	13,000	------	36.0
	-196	------	------	----	----	------	------------	------------	-----	------	------	------	38.0
	-314	31,900	20,600	42.0	73.5	------	------------	------------	59.7	------	------	------	42.5
	-321	------	------	----	----	------	------------	------------	-----	23,000	------	------	----
	-423	------	------	----	----	------	------------	------------	-----	------	------	------	38.5
24S-T4	77	69,900	48,500	20.0	30.5	46,150	10.87	10.75×10^{-6}	143	------	26,000	20,000	5.5
	-108	72,300	51,100	21.0	25.5	49,700	11.11	13.41	151	------	------	25,000	5.5
	-196	------	------	----	----	------	------------	------------	-----	------	------	------	6.0
	-314	87,300	63,100	21.5	20.5	57,350	11.97	13.22	166	------	------	------	6.0
	-321	------	------	----	----	------	------------	------------	-----	------	43,000	------	----
	-423	------	------	----	----	------	------------	------------	-----	------	------	------	6.0
61S-T6	77	44,200	38,400	19.0	51.0	------	10.08	------------	104	25,000	20,000	------	9.0
	-108	47,800	41,400	21.0	50.5	------	10.62	------------	114	------	23,000	------	10.2
	-196	------	------	----	----	------	------------	------------	-----	------	------	------	10.0
	-314	56,000	42,500	25.5	47.0	------	10.77	------------	130	------	------	------	11.0
	-321	------	------	----	----	------	------------	------------	-----	38,000	------	------	----
	-423	------	------	----	----	------	------------	------------	-----	------	------	------	11.5
75S-T6	77	83,900	72,200	13.5	28.0	72,750	10.20	10.43	181	33,000	------	28,000	4.0
	-108	88,600	78,100	12.5	22.5	78,300	10.79	12.28	193	------	------	30,000	5.0
	-196	------	------	----	----	------	------------	------------	-----	------	------	------	5.0
	-314	99,500	89,500	12.0	15.0	83,200	11.55	2.90	214	------	------	------	6.0
	-321	------	------	----	----	------	------------	------------	-----	58,000	------	------	----
	-423	------	------	----	----	------	------------	------------	-----	------	------	------	5.0

"Vickers hardness tests were made at room temperature, -78° C [-108° F] and -192° C [-314° F] (liquid air). The hardness of all the materials increased with falling temperatures."

The data show increases in elongation and moderate decreases in reduction of area at the low temperatures with the exception of 75S-T6 where the elongation shows a moderate decrease and the reduction of area a bigger decrease.

Modulus values both in tension and compression are somewhat higher at the low temperatures.

The compressive yield strengths of 24S-T4 and 75S-T6 show increases similar to those of tensile yield strength at -108° and -314° F.

61. Results of Tensile Tests of Various Aluminum Alloys at -18°, -112° and -320° F Made at the Aluminum Research Laboratories. (Unpublished data).

Tests have been made of 29 alloys, including both wrought and cast, in various tempers and commercial forms at -18°, -112°, and -320° F. Most of the commercial alloys of the heat-treatable and not-heat-treatable types are included. In addition, tensile tests have been made at -320° F of the weld metal in some welded joints.

Tables I, II, and III on the following pages show the results of these tests.

TABLE I.- WROUGHT ALLOYS

Alloy, temper, and form	Temperature (°F)	Tensile strength (psi)	Yield strength (psi) (1)	Elongation in 4 diameters (percent)	Reduction of area (percent)
2S-O, rolled and drawn rod	75	13,000	5,000	42.5	76.4
	-18	13,500	5,000	43.0	76.4
	-112	14,800	5,300	47.5	77.0
	-320	24,600	6,200	56.0	74.4
2S-H12, rolled and drawn rod	75	16,000	14,300	23.2	76.2
	-18	16,700	14,400	23.2	76.3
	-112	18,000	15,000	27.0	77.4
	-320	27,400	16,600	45.8	74.8
2S-H18, rolled and drawn rod	75	22,200	20,200	16.0	59.8
	-18	23,000	20,800	15.2	59.4
	-112	24,200	21,200	18.0	65.3
	-320	32,600	24,200	35.2	67.0
3S-O, rolled and drawn rod	75	15,600	6,000	43.0	80.6
	-18	16,600	6,100	44.0	80.6
	-112	19,000	7,300	45.0	79.9
	-320	32,200	8,600	48.8	71.2
3S-F, plate	75	17,400	8,200	33.9	65.0
	-18	-------	------	----	----
	-112	-------	------	----	----
	-320	35,400	10,400	41.8	56.4
3S-H12, rolled and drawn rod	75	19,900	18,600	24.0	76.1
	-18	21,200	18,800	23.5	75.2
	-112	23,200	19,600	27.2	75.8
	-320	35,600	22,900	40.0	69.0
3S-H18, rolled and drawn rod	75	28,400	26,200	15.0	63.5
	-18	30,000	26,800	15.0	64.4
	-112	31,500	28,200	16.5	66.5
	-320	41,900	32,000	32.0	62.3
4S-O, rolled and drawn rod	75	28,500	10,800	25.0	64.0
	-18	29,400	11,000	28.5	65.7
	-112	31,400	11,400	33.0	66.2
	-320	46,800	13,600	40.5	59.0
4S-F, plate	75	30,100	16,100	22.0	58.2
	-18	-------	------	----	----
	-112	-------	------	----	----
	-320	48,200	19,800	34.0	45.5
4S-H34, rolled and drawn rod	75	34,900	31,200	12.0	45.1
	-18	35,300	31,000	13.0	47.6
	-112	38,000	33,000	15.5	48.3
	-320	-------	------	----	----
4S-H38, rolled and drawn rod	75	43,400	38,000	13.2	44.9
	-18	44,300	38,000	15.0	48.3
	-112	46,500	39,000	17.0	49.2
	-320	60,000	46,100	22.9	45.7
52S-O, rolled and drawn rod	75	29,100	14,300	33.2	72.0
	-18	29,200	14,400	35.8	74.2
	-112	30,600	14,300	40.8	76.4
	-320	44,800	16,800	50.0	69.0
52S-F, plate	75	26,100	9,400	31.2	70.1
	-18	-------	------	----	----
	-112	-------	------	----	----
	-320	42,400	11,100	49.0	69.6
52S-H32, rolled and drawn rod	75	32,200	24,400	21.7	71.9
	-18	32,900	24,100	22.9	73.1
	-112	34,800	24,300	26.3	73.8
	-320	50,700	28,400	37.7	63.6
52S-H38, rolled and drawn rod	75	40,100	34,200	16.6	59.1
	-18	40,700	33,800	18.3	63.2
	-112	42,400	34,300	20.6	64.5
	-320	57,900	39,800	30.9	57.4
11S-T3 rolled and drawn rod	75	56,600	46,500	16.3	41.3
	-18	56,900	46,400	16.0	41.9
	-112	57,500	47,500	16.7	43.9
	-320	73,500	55,800	26.0	36.0
11S-T8, rolled and drawn rod	75	56,800	43,500	14.2	36.6
	-18	59,000	44,300	14.0	35.9
	-112	61,100	45,900	14.7	38.2
	-320	72,300	51,500	15.3	36.0
14S-O, rolled and drawn rod	75	26,000	9,900	26.5	44.8
	-18	26,400	9,400	27.2	48.3
	-112	26,900	10,100	29.2	50.6
	-320	39,000	11,500	35.8	47.0
14S-T4, rolled and drawn rod	75	65,500	41,900	24.8	37.5
	-18	67,700	42,300	25.2	39.2
	-112	68,400	43,800	25.4	37.4
	-320	84,200	55,300	27.2	26.6
14S-T4, forging	75	65,600	38,700	23.0	28.0
	-18	68,300	39,000	21.7	27.5
	-112	68,100	40,800	20.8	29.0
	-320	78,800	50,300	17.0	20.3
14S-T4, thick extrusion	75	77,200	56,200	17.2	23.4
	-18	80,100	56,500	17.3	18.2
	-112	80,900	57,800	16.7	19.2
	-320	100,700	76,600	15.2	14.9
14S-T6, rolled and drawn rod	75	69,300	61,700	13.2	30.9
	-18	71,000	62,600	13.0	29.0
	-112	72,500	64,200	13.4	27.9
	-320	83,200	71,200	14.8	26.3
14S-T6, forging	75	67,800	60,200	12.3	25.6
	-18	69,500	61,500	11.2	23.6
	-112	70,300	61,800	13.6	24.1
	-320	80,700	68,100	10.4	13.7
14S-T6, thick extrusion	75	76,800	69,400	10.1	21.4
	-18	78,700	70,700	9.3	21.1
	-112	80,500	72,800	10.0	22.1
	-320	95,400	86,500	10.4	17.3
17S-T4, rolled and drawn rod	75	60,600	38,700	23.2	37.2
	-18	62,500	39,400	24.0	37.2
	-112	63,800	40,800	25.5	35.7
	-320	78,400	51,400	28.3	28.8

[1]Offset, 0.2 percent.

TABLE I.- WROUGHT ALLOYS - Concluded

Alloy, temper, and form	Temperature (°F)	Tensile strength (psi)	Yield strength (psi) (1)	Elongation in 4 diameters (percent)	Reduction of area (percent)	Alloy, temper, and form	Temperature (°F)	Tensile strength (psi)	Yield strength (psi) (1)	Elongation in 4 diameters (percent)	Reduction of area (percent)
17S-T4,	75	75,900	54,200	14.0	17.2	53S-0,	75	15,500	6,000	40.5	72.1
thick	-18	78,300	54,400	16.8	19.8	rolled and	-18	16,400	6,400	42.0	71.7
extrusion	-112	79,500	56,200	18.0	16.3	drawn rod	-112	18,400	7,300	42.5	71.5
	-320	100,000	76,700	14.4	17.0		-320	31,600	8,700	50.0	63.2
18S-T61	75	63,300	51,200	12.4	21.0	53S-H36,	75	25,200	23,800	12.8	46.8
	-18	65,200	51,000	14.3	22.0	rolled and	-18	27,200	25,000	13.0	49.6
	-112	66,200	52,200	14.4	21.3	drawn rod	-112	29,100	26,000	15.5	50.4
	-320	75,000	56,300	14.6	18.4		-320	41,000	30,200	27.5	50.1
B18S-T61	75	59,200	43,400	14.5	24.1	53S-T4,	75	36,200	20,100	30.0	56.4
	-18	59,400	43,400	15.[illegible]	26.6	rolled and	-18	37,600	20,800	32.0	55.9
	-112	61,100	44,100	17.3	30.7	drawn rod	-112	39,900	21,100	32.5	54.8
	-320	73,200	53,500	20.0	29.0		-320	52,700	26,900	37.5	44.3
24S-0,	75	30,600	11,200	23.0	39.3	53S-T6,	75	37,200	29,200	23.0	53.8
rolled and	-18	31,200	11,400	22.7	41.6	rolled and	-18	39,400	30,000	24.5	52.8
drawn rod	-112	32,800	12,300	24.9	43.2	drawn rod	-112	42,000	31,700	25.5	52.8
	-320	46,000	15,100	30.3	39.8		-320	53,600	36,800	30.3	48.4
24S-T4,	75	70,100	43,700	23.3	31.8	61S-0,	75	17,600	6,400	34.5	73.2
rolled and	-18	72,600	44,200	24.4	33.1	rolled and	-18	18,400	6,700	36.0	73.5
drawn rod	-112	74,100	46,400	25.3	30.8	drawn rod	-112	20,000	7,200	40.5	74.4
	-320	89,000	58,100	26.7	26.3		-320	33,100	8,400	48.5	66.8
24S-T4,	75	83,200	63,500	12.8	14.4	61S-T4,	75	40,300	21,800	30.5	57.4
thick	-18	83,200	63,800	13.3	15.5	rolled and	-18	41,700	22,500	31.5	56.0
extrusion	-112	85,200	66,500	13.3	15.9	drawn rod	-112	44,100	23,200	32.5	54.1
	-320	106,600	86,000	11.0	11.9		-320	57,900	29,400	36.6	41.3
24S-T36,	75	73,400	62,000	16.0	16.6	61S-T6,	75	46,000	39,500	21.8	56.4
rolled and	-18	75,300	61,500	18.0	26.4	rolled and	-18	48,100	40,600	21.5	52.5
drawn rod	-112	75,500	63,600	16.0	24.8	drawn rod	-112	50,400	41,700	22.5	53.7
	-320	-------	------	----	----		-320	61,200	46,000	26.5	46.5
24S-T36,	75	71,600	54,000	14.0	21.6	61S-T6,	75	43,800	39,300	16.0	41.5
plate	-18	73,200	54,500	17.3	23.0	plate	-18	-------	------	----	----
	-112	74,500	56,000	18.0	21.2		-112	-------	------	----	----
	-320	88,200	66,100	17.6	19.0		-320	55,500	45,500	21.4	42.2
24S-T6,	75	72,600	58,100	14.5	25.8	63S-0,	75	12,900	6,500	38.5	78.8
rolled and	-18	72,800	58,300	12.7	21.5	extrusion	-18	14,200	6,200	43.0	79.7
drawn rod	-112	74,500	60,100	13.3	22.0		-112	15,700	7,300	45.0	79.0
	-320	87,400	70,000	14.0	19.7		-320	-------	------	----	----
27S-T6,	75	64,900	53,800	12.0	28.3	63S-T5,	75	28,000	22,800	20.0	71.0
rolled and	-18	67,600	55,800	11.4	24.8	extrusion	-18	28,200	22,600	22.0	79.1
drawn rod	-112	70,500	58,300	13.3	27.2		-112	29,000	22,400	23.0	81.2
	-320	78,700	60,100	15.4	29.4		-320	-------	------	----	----
32S-T6,	75	56,200	46,700	10.0	18.2	63S-T6,	75	35,000	30,500	16.5	43.7
rolled and	-18	58,000	46,000	8.8	17.1	extrusion	-18	36,000	31,000	16.0	35.9
drawn rod	-112	59,500	45,500	9.5	16.2		-112	38,100	32,100	17.0	37.6
	-320	68,200	49,000	11.3	16.8		-320	-------	------	----	----
51S-T6,	75	43,000	33,500	17.7	29.9	75S-0,	75	34,100	15,200	19.2	39.9
rolled and	-18	45,200	33,900	16.6	28.4	rolled and	-18	35,300	15,200	19.2	41.4
drawn rod	-112	47,200	36,000	16.0	24.8	drawn rod	-112	37,100	16,300	21.2	40.2
	-320	56,200	39,700	15.4	17.5		-320	49,700	19,200	23.8	36.0
A51S-T6,	75	47,100	40,700	19.4	46.9	75S-T6,	75	81,300	70,300	15.0	29.1
rolled and	-18	50,000	42,300	19.0	43.4	rolled and	-18	82,700	71,200	15.3	26.2
drawn rod	-112	52,300	43,800	19.0	42.5	drawn rod	-112	85,400	73,300	15.3	23.6
	-320	-------	------	----	----		-320	97,000	82,600	16.0	20.1
A51S-T6,	75	46,500	43,200	15.2	38.8	75S-T6,	75	91,000	83,800	10.7	16.3
forging	-18	47,300	44,700	12.0	34.0	extrusion	-18	94,600	86,500	8.7	12.9
	-112	47,600	44,200	14.9	38.7		-112	96,600	89,400	9.6	11.9
	-320	55,700	48,200	18.3	34.7		-320	116,100	109,100	7.2	9.5

[1]Offset, 0.2 percent.

TABLE II.- SAND-CAST ALLOYS

Alloy and temper	Temperature (°F)	Tensile strength (psi)	Yield strength (psi) (1)	Elongation in 4 diameters (percent)
12, as-cast	75	25,300	14,900	1.8
	-112	25,500	14,000	1.5
47, as-cast	75	27,300	12,400	10.0
	-112	29,100	13,800	6.8
A108, as-cast	75	24,800	20,000	.8
	-112	24,900	20,700	1.0
109, as-cast	75	26,600	22,600	0
	-112	27,800	24,000	.5
121, as-cast	75	23,800	------	.2
	-112	22,700	------	.5
122-T4	75	40,700	------	.7
	-112	42,200	------	0
195-T62	75	43,600	------	.5
	-112	44,100	------	1.0
196-T62	75	49,900	------	0
	-112	52,900	------	.2
355-T51	75	27,000	23,400	1.0
	-18	27,800	23,200	1.5
	-112	29,700	23,900	1.5
	-320	32,800	25,400	1.2
406, as-cast	75	18,500	8,200	13.0
	-112	19,800	8,700	9.0
645, as-cast	75	37,800	------	1.2
	-112	42,700	------	1.0

[1]Offset, 0.2 percent.

TABLE III.- ALL-WELD SPECIMENS FROM WELDED PLATE

Alloy and temper of plate	Thickness of plate (in.)	Filler metal	Location of specimen in weld	Temperature (°F)	Tensile strength (psi)	Yield strength (psi) (a)	Elongation in 2 in. (percent)	Reduction of area (percent)
Argon-shielded tungsten-arc welds								
3S-F	2	2S	Face half	75	[b]15,000	[b]5,300	[b]16.0	[b]42.2
				-320	33,000	7,800	34.5	43.8
			Root half	75	16,200	6,100	30.0	56.3
				-320	32,600	8,500	24.5	34.7
4S-F	1	2S	Center	75	18,400	8,300	26.8	52.0
				-320	31,100	10,100	22.5	30.8
4S-F	1	43S	Center	75	22,000	10,000	11.2	18.0
				-320	34,400	12,800	11.5	13.6
52S-F	2	43S	Face half	75	20,200	9,200	8.0	16.0
				-320	28,300	12,300	(c)	(c)
			Root half	75	22,300	9,200	13.0	21.0
				-320	31,000	12,200	8.0	12.4
61S-T6	1	43S	Center	75	33,000	25,800	4.0	6.5
				-320	39,200	32,000	2.6	5.0
Metallic-arc welds								
3S-F	$2\frac{1}{2}$	3S	Face half	75	14,400	7,600	5.8	12.4
				-320	24,700	10,600	7.0	13.6

[a]Offset, 0.2 percent.
[b]Fracture revealed considerable porosity.
[c]Specimen fractured outside of gage length.

The results of tests of wrought alloys in table I show that tensile strengths and yield strengths are only slightly higher at temperatures as low as -112° F. At -320° F, however, the increase in these properties is considerable, ranging up to about 75 percent. An exception is the alloy 32S, which has a high silicon content; its properties are less advantageously affected by the low temperatures.

In general, the elongations of the wrought alloys are higher, especially at -320° F. However, in the case of a few alloys, especially in the form of extrusions, the elongation is slightly lower, particularly at -320° F.

Although many of the alloys show increasing values for reduction of area with decrease in temperature, the higher strength alloys usually exhibit decreasing values, the decreases amounting to as much as 1/5 at -320° F.

In table II it will be noted that only one of the sand-cast alloys was tested at -18° and -320° F. The remaining alloys were tested only at -112° F. The results of these tests show only slightly higher tensile and yield strengths at -112° F for most of the alloys. The one alloy tested at -320° F indicates rather clearly that the strengths are higher at this temperature. Elongations and reductions of area show little if any change at the low temperatures, with the exception of 47 and 406 alloys where elongations and reductions of area are comparatively high at 75° F. In these cases there are considerable decreases at -112° F.

Results of tensile tests of the weld metal of arc-welded plates at -320° F as listed in table III show consistent increases of both tensile and yield strengths, but the changes in elongation and reduction-of-area values are not consistent.

62. Results of Tensile Tests of Notched and Unnotched Large 61S-T6 Plate Specimens at Low Temperatures Made at the Aluminum Research Laboratories. (Unpublished data.)

In this group of tensile tests four types of 12-inch-wide specimens of the full thickness of $\frac{3}{4}$-inch 61S-T6 plate were prepared. One type contained no stress-raisers. The second type contained saw cuts emanating on either side of a $\frac{3}{4}$-inch hole drilled in the center of the specimen, the saw cuts being made with a jeweler's saw and total width of the notch being 3 inches. The third type had a single 3-inch hole at the center. The fourth type had three 1-inch-diameter holes drilled along the transverse center line of the specimen, and idle rivets driven into the holes.

The results obtained are shown in the table on the next page. They indicate that the tensile strengths of notched and plain specimens of these types are higher at temperatures ranging from -33° to -60° F than at room temperature.

TENSILE TESTS OF PLAIN AND NOTCHED SPECIMENS OF 61S-T6 PLATE

Description of notch	Temperature at failure (°F)	Ultimate stress on net section (psi)	Av. reduction in thickness at fracture (percent)	Final elongation (in.)		Energy absorbed in 39.5-in. gage length (in.-lb)	
				In 9 in.	In 39.5 in.	To maximum load	To fracture
Plain (no notch)	127	42,200	16.4	1.852	3.23	854,000	1,135,000
	[a]-38	46,100	32.2	[a]1.5	3.48	1,127,000	1,315,000
Hole with saw cuts	125	38,700	4.2	.372	.372	17,100	49,800
	80	39,900	4.2	.290	.290	18,100	42,200
	-35	41,600	6.0	.377	.377	21,000	57,800
	-60	40,900	4.0	.375	.375	19,300	56,000
3-in.-diameter hole	125	42,900	12.4	.557	.557	92,900	124,800
	-33	46,400	11.5	.485	.485	101,500	113,500
Three 1-in.-diameter holes with rivets	-45	51,100	18.8	.422	.422	77,400	109,000

[a]Fractured outside of cold region; temperature at point of fracture not measured.

Variations of temperature in the range covered by these tests were accompanied by no appreciable decrease in ductility of these specimens, as indicated by the final elongations and reductions in thickness at the fractures, and by the energy-absorbing capacity.

Shear fractures were obtained in notched as well as plain specimens at the low temperatures. The fractures are classed as ductile since the reductions in thickness at the fractures are greater than 2 percent.

63. Results of Impact Tests of Some Extruded Aluminum Alloys at Low Temperatures Made at the Aluminum Research Laboratories. (Unpublished data.)

Impact tests of full-sized specimens of 4-inch extruded I-beams of 14S-T4, 14S-T6, 61S-T6, 61S-T62, and 75S-T6 have been made. Izod impact tests of specimens taken from these I-beams were also made for comparison.

The tests of the full-sized I-beams were made of beams unsupported over a 30-inch span to find the minimum height of drop of a 250-pound tup to strike the middle of the span and produce complete fracture of the tension flange. Two open $\frac{5}{8}$-inch-diameter holes in the tension flange at the center of the span served as stress-raisers.

The results of the tests, which were made at three temperatures, were as follows:

Alloy and temper	Height of drop, in., at - (250-lb tup, 30 in. span)		
	85° F	-20° to -30° F	-106° to -114° F
14S-T4	23.0	26.5	31.0
14S-T6	22.0	25.0	----
61S-T6	25.5	26.5	----
61S-T62	35.0	35.0	34.0
75S-T6	23.0	25.5	25.0

Results of the Izod tests made of specimens from the same I-beams were as follows:

Alloy and temper	Izod impact value, ft-lb, at -	
	Room temperature	-112° F
14S-T4	14.5	15.2
14S-T6	4.6	5.0
61S-T6	[a]14.0	[a]13.4
61S-T62	[a]24.6	[a]26.4
75S-T6	2.4	2.0

[a]Results not definitive because fractures were not complete.

The results of the two types of tests demonstrate that the strengths of the alloys, in the presence of stress concentrations and under impact loading, are not adversely affected by low temperatures.

64. Results of Charpy Impact Tests of Welded Plate at Room Temperature and at -320° F, as reported by Dr. M. Gensamer, Pennsylvania State College. (Private communication.)

Charpy impact tests were made of two pairs of argon-shielded tungsten-arc welded 3S-F plate, 1/2 inch thick. One pair was welded using 2S filler wire and the other pair using 43S filler wire. One group of specimens was cut parallel and adjacent to the weld, and the second group was cut across the weld with the notches on the center line of the weld.

Results of tests were as follows:

Specimen	Temperature (°F)	Charpy impact value (ft-lb)
Original 3S-F plate		
Across grain	78 -320	[a]17.5 [a]17.6
3S-F plate welded with 2S filler wire		
Across grain, parallel and adjacent to weld	78 -320	[a]20.2 [a]20.3
Across weld with notch at center of weld	78 -320	[b]10.1 [c]10.4
3S-F plate welded with 43S filler wire		
Across grain, parallel and adjacent to weld	78 -320	[a]19.8 [a]18.7
Across weld with notch at center of weld	78 -320	4.8 4.8

[a]Results of tests not definitive because failures were not complete.
[b]Three out of four specimens failed to break.
[c]Two out of four specimens failed to break.

In a second group of Charpy impact tests, welded 3S, 4S, 52S, and 61S plates were tested, with the following results:

Alloy and temper	Thickness (in.)	Type of arc	Weld wire	Location of specimen	Impact strength, ft-lb, at -	
					Room temperature	-320° F
3S-F	$2\frac{1}{2}$	Metallic	3S	Parent metal Adjacent to weld In weld	25.4 26.2 6.3	23.4 23.2 5.3
3S-F	2	Tungsten	2S	Parent metal Adjacent to weld In weld	28.2 27.0 13.6	25.1 25.1 16.6
4S-F	1	Tungsten	43S	Parent metal Adjacent to weld In weld	17.2 18.3 14.1	16.8 17.2 14.1
4S-F	1	Tungsten	2S	Parent metal Adjacent to weld In weld	17.0 17.4 3.6	16.4 16.9 2.6
52S-F	2	Tungsten	43S	Parent metal Adjacent to weld In weld	30.9 31.0 3.5	27.6 28.2 3.0
[a]61S	1	Tungsten	43S	Parent metal Adjacent to weld In weld	5.6 5.8 1.4	6.8 6.6 1.3
[b]61S	1	Tungsten	43S	Parent metal Adjacent to weld In weld	13.8 12.6 3.9	13.3 12.8 2.6

[a]Heat-treated and aged after welding (welded in -F temper).
[b]Heat-treated and aged before welding.

The author concludes:

"There are no indications that the specimens tested suffer any loss of ductility on lowering the temperature from room temperature to about -310° F."

65. Results of Charpy Impact Tests of 61S-T6 Plate at Room Temperature and -30° F, as reported by Dr. M. Gensamer, Pennsylvania State College. (Private communication.)

Charpy impact tests of $\frac{3}{4}$-inch-thick 61S-T6 plate have been made. The following results were obtained:

Direction of specimen	Impact strength, ft-lb, at -	
	88° F	-30° F
Longitudinal[1]	6.3	7.2
Transverse[1]	4.3	4.3

[1]The notch was cut normal to the surface of the plate.

These results show at least as much energy absorption at a temperature of -30° F as at room temperature.

66. Results of Tear Tests of 61S-T6 Plate at -50, -80 and -110° F. (Unpublished data.)

Tear tests were made of $\frac{3}{4}$-inch 61S-T6 plate. The specimens were supported on pins mounted in pulling shackles and subjected to static tensile loading with the notch perpendicular to the line of application of load.

The following results were reported:

Direction of specimen	Temperature (°F)	Energy to start tear (ft-lb)	Energy to propogate tear (ft-lb)	Total energy (ft-lb)	Maximum load (lb)
Longitudinal	77	199	224	423	28,450
	-50	213	181	394	29,400
	-80	194	133	327	29,500
	-110	191	99	296	29,950
Transverse	77	107	36	143	22,000
	-50	138	15	153	25,300

The results of these tests lead to the following conclusions:

(1) There is no evidence of a so-called transition temperature zone which, in the case of steel, characterizes the change from ductile- to brittle-type fracture.

(2) With decrease in test temperature, the energy values to start tearing showed a moderate increase in the case of the transverse specimens but remained relatively constant for the longitudinal specimens.

(3) With decreasing temperature the energy values to propogate tearing in the longitudinal specimens decreased considerably from 77° F to -110° F.

(4) With decreasing temperature, the energy values to propogate tearing in the transverse specimens showed a moderate decrease.

(5) There was some tendency for the maximum load to increase with reduction in test temperature, particularly in the transverse specimens.

GENERAL CONCLUSIONS

A review of the data presented, and the conclusions expressed by the authors of the articles reviewed, leads to the following general conclusions regarding the aluminum alloys used commercially in this country:

1. The tensile and yield strengths of aluminum alloys are higher at low temperatures than at room temperature. Wrought alloys show greater improvement at low temperatures than do cast alloys.

2. There is no evidence of embrittlement of aluminum alloys at low temperatures. The wrought alloys in general show improved elongation at low temperatures while most of the cast alloys show either a slight increase in elongation or no appreciable change.

3. The reduction of area generally decreases somewhat at low temperatures, a fact which, taken together with the fact that there is either an increase or no change in over-all elongation, shows that the uniform elongation (not including the localized high elongation in the vicinity of the fracture) increases more than is indicated merely by the reported values of elongation.

4. The modulus of elasticity increases as the temperature is lowered below normal room temperature.

5. The hardness of aluminum alloys increases as the temperature is lowered below normal room temperature.

6. The notch sensitivity of aluminum alloys, as measured by the usual types of so-called impact tests, is not adversely affected by low temperatures.

7. The fatigue strength of aluminum alloys is higher at low temperatures than at normal room temperature.

Aluminum Research Laboratories
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